Quantifying Phosphorus Loss In Runoff From Grazing Cattle

Final Report for GLCI Research Grant Project 10301

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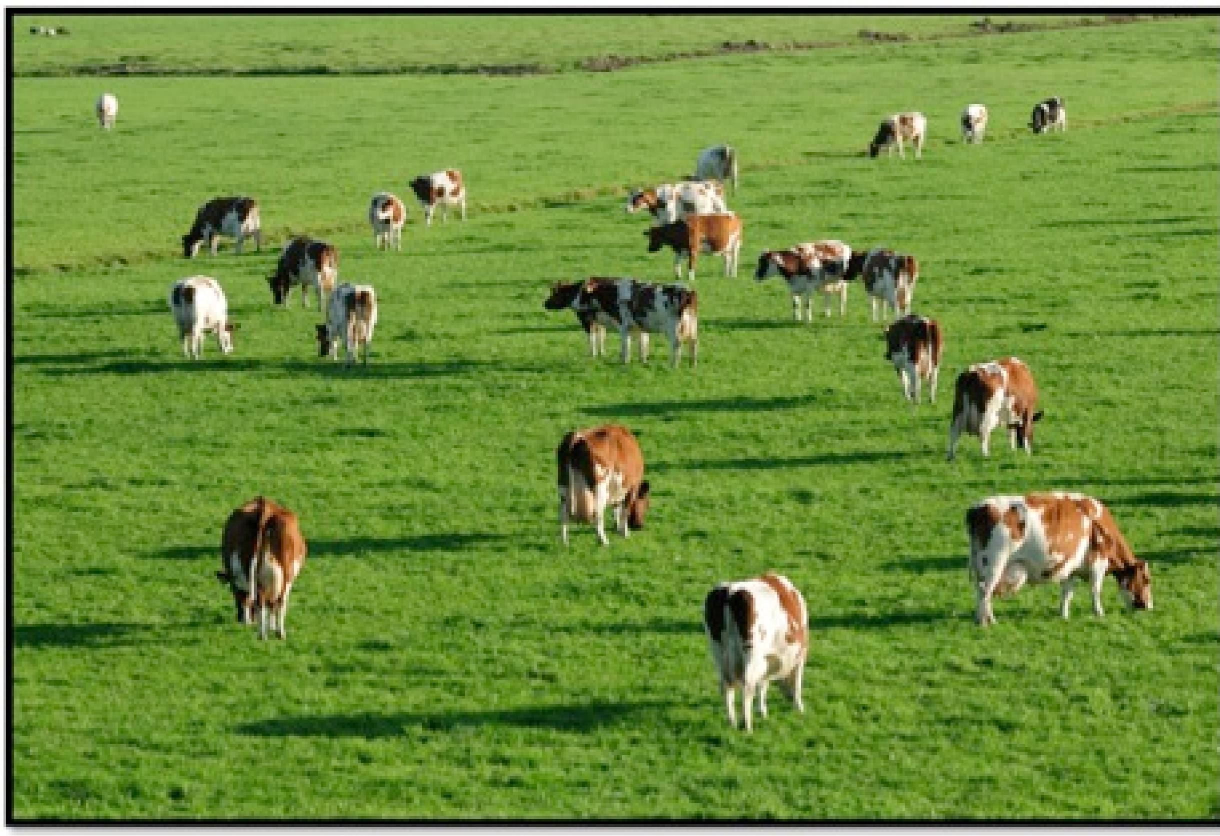

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Introduction and Objectives

Non-point source pollution of surface waters by phosphorus (P) can accelerate eutrophication and limit water use for drinking, recreation, and industry. Because P loss from agricultural systems via surface runoff has consistently been identified as a non-point pollution source, there is a need to quickly and accurately quantify runoff P loss from farms, identify the major sources of farm P loss, and develop management practices to reduce P loss. For dairy farms, possible sources of runoff P loss include cropland, grazed pastures, and outside cattle holding areas, such as feedlots, barnyards, exercise lots, or over-wintering lots.

Because quantifying runoff P loss from all these sources on a dairy farm through physical monitoring is expensive and lengthy (likely a multi-year project), simulation models are seen as more rapid, cost effective ways to estimate P loss. Existing models include field-scale tools like the Wisconsin P Index (WI PI), farm-scale models like the Inegrated Farm Systems Model (IFSM) (Sedorovich et al., 2007), and field to watershed-scale models like the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) or the Agricultural Policy/Environmental eXtender (APEX) (Gassman et al., 2010). However, none of these tools is likely appropriate for simulating P loss via surface runoff from grazed pastures. The WI PI does not simulate grazed pastures; IFSM apparently does not simulate P loss from grazing animal dung; and SWAT and APEX do not simulate manure or dung on the soil surface, which precludes adequate simulation of P loss from grazing dung. Therefore, it is clear that better tools are needed to simulate P loss from dairy farms in general and cattle-grazed pastures in particular. However, developing simulation tools for pastures first requires conducting research that monitors P loss in runoff from grazed pastures. Such studies can supply the data needed to develop the simulation tools.

Worldwide, there has been adequate research conducted to monitor P loss in runoff from grazed pastures (Capece et al., 2007; Dougherty et al., 2008; Edwards et al., 2000; Haan et al., 2006; Halliwell et al., 2000; McDowell et al., 2007; Nash et al., 2000; O'reagain et al., 2005; Owens and Shipitalo, 2006). However, considerably less research of runoff from pastures has been conducted compared to P loss from cropland, and most of it has been conducted outside of the U.S. In the U.S., only limited field-scale, natural rainfall, pasture runoff research has been conducted where the major source of manure addition is through grazing animals (Capece et al., 2007; Chichester et al., 1979; Menzel et al., 1978; Olness et al., 1975; Owens and Shipitalo, 2006; Schepers and Francis, 1982). The majority of research has been conducted in Australia, New Zealand, and the United Kingdom. Overall, there is a need for pasture runoff monitoring research for different systems in the U.S., especially for developing P loss simulation models.

The objectives of our project were to: i) monitor P loss in runoff from eight beef and dairy grazed pastures at the UW Platteville Pioneer Farm, ii) use the runoff data to validate the ability of our Annual P Loss Estimator (APLE) model to predict P loss in runoff from grazed pasture, and iii) use APLE to simulate annual P loss from four WI grazing farms and determine relative impact of pastures to whole-farm P loss. One major purpose of the study is to help improve the SNAP+ nutrient management software for use with cattle pastures in WI. Information in this report covers the time period from August, 2010 until April, 2012.

Methods and Materials

Runoff monitoring at Pioneer Farm

Runoff basin establishment, runoff and soil sampling

We established eight, hydrologically isolated basins ranging in size from 0.7 to 1.0 acre in an existing cattle pasture at the UW-Platteville Pioneer Farm. The basins were oriented so that four are on a south-facing slope (5-8%) and four are on a north-facing slope, with a ridge separating the two groups (Fig. 1).

We installed runoff collection shelters at the outlet of each basin. Each runoff collection location consisted of wooden wing walls that channeled surface runoff into an H-flume (details) where flow was measured (details) and runoff samples were collected automatically on a flow-weight basis with ISCO samplers (details). Samples were pumped into 1-liter containers and collected within 24 h. The sampling system was inside a covered shelter and was equipped with radiant heaters so runoff could be collected year round. Rainfall data were collected with existing equipment at the Pioneer farm.

We also collected soil samples from each pasture basin from 0-1 and 0-6 inches to assess the historical P accumulation in soils and the degree of P stratification (i.e., greater P in the 0-1 layer due to historical surface manure applications). Soil samples were analyzed by routine analysis (pH, organic matter, Bray-1 P) at the UW Soil and Plant Analysis Lab.

Runoff analysis

The sampling protocol described above generated single composite runoff sample for each event for each runoff basin. We analyzed all runoff samples for total sediment, total nitrogen (N) and P, and dissolved P, ammonium (NH_4), and nitrate (NO_3) at the USDA-ARS Dairy Forage Research Center lab in Madison, WI. Total sediment was measured by drying a known quantity (~50 mL) of a well shaken runoff sample in an oven and calculating sediment content (g/L) as the difference in the weight of the sample before and after drying. Runoff samples were filtered through 0.45 um filters, and filtered samples were analyzed for dissolved reactive P (DRP) by the procedure of Murphy and Riley (1962). Filtered samples were also analyzed for dissolved NH_4, and NO_3 using QuickChem Methods 12-107-06-2-A (ammonium) and 12-107-04-1-B (nitrate) on a Lachat automated N analyzer. To measured total N (TN) and P (TP), unfiltered samples were digested in an autoclave with ammonium persulfate, with digested samples analyzed for TN and TP by the same methods as the filtered samples (Langner and Hendrix, 1982). Only P data are discussed in this report.

Pasture management at Pioneer Farm

The eight runoff basins were within existing pastures grazed by beef and non-lactating dairy cattle. The southern four basins were within an 18-acre pasture and were grazed by beef cattle, and the northern four basins were within a 15-acre pasture grazed by dairy cattle. Thus, the four runoff basins in each group all received the same management. In general, cattle were given free access to the pastures starting in mid-May until mid-November, with numbers of dairy cattle ranging between 14 to 34 and beef cattle between 18 to 28.

The statistical pasture runoff monitoring strategy is one of a paired watershed approach (Clausen et al., 1996; Jokela and Casler, 2011). In this approach, at least two watersheds are monitored during a calibration period. The duration of the calibration depends on how many runoff events are observed, but likely lasts at least one year. Runoff data from paired watersheds during this period are correlated to each other to determine the relationship in the hydrologic and nutrient export response to the same relative weather. Once a relationship is established, management on one (or more if there are more than two) watershed is changed. Runoff and nutrient export continue to be monitored for a similar time period as the calibration period. The impact of the management change can then be quantified by determining the magnitude of the change in the hydrologic and nutrient export response relationship between the watersheds.

The information in this report is for the calibration period only. Thus, there is no information on the impact of specific pasture management strategies. However, such evaluation of pasture management is intended for future research on these runoff basins.

Determination of event and annual P loads

To determine event loads from each pasture basin, we multiplied the concentration of sediment, DRP, and TP (mg/L) in runoff samples by the runoff amount from each basin (L/ha) to determine a load (kg/ha). Because all pastures were essentially managed the same, we averaged loads across all eight basins (or fewer depending on whether or not all basins had runoff for a given event) for a single load per event. For annual sediment or P loads, we summed all event loads for a given 365-d period, which in this project was summer of one year to summer the next year.

Validation of APLE for runoff P loss from pastures

APLE description

APLE is a Microsoft Excel spreadsheet model that runs on an annual time-step and simulates sediment bound and dissolved P loss in surface runoff. It is intended to simulate edge-of-field P loss for uniform fields of several hectares in size, or smaller. APLE has been tested for its ability to reliably predict P loss in runoff for systems with machine-applied manure and for soil P cycling (Vadas et al., 2007). APLE is available to download at the USDA-ARS Dairy Forage Research Center website (http://ars.usda.gov/Services/docs.htm?docid=21763), along with Theoretical Documentation and a User's Manual that describe the model in detail. Here, we present a summary of the model and our effort to validate it for P loss in runoff from grazed pastures.

APLE is intended to be user-friendly and does not require extensive input data to operate. All data are entered directly into the spreadsheet. User-input data include:

- Soil properties, including depth of two topsoil layers, Mehlich-3 soil test P, soil clay content, and soil organic matter content
- Surface area of the field
- Annual precipitation, runoff, and erosion amounts
- Total annual crop P export

- Total number of annual animal days in the field, including beef cattle and calves, dairy lactating and dry cows, and dairy heifers and calves.
- Manure amount applied, manure % solids, manure total P content, % of manure total P that is water extractable P, % of manure incorporated, and depth of incorporation.
- Amount of fertilizer P applied, % fertilizer incorporated, and depth of incorporation.
- Degree of soil mixing by tillage or biological processes.

APLE simulates P loss in runoff from animal manure, applied either by machine or by grazing beef or dairy cattle; fertilizer; and soils, in both a sediment-bound form in erosion and a dissolved form in runoff.

APLE estimates sediment P loss in runoff as:

$$\textit{Sediment P Loss} = (\textit{Eroded Sediment})(\textit{Soil Total P})(\textit{P Enrichment Ratio})(10^{-6}) \qquad [1]$$

where:
Sediment P Loss: Annual P loss in runoff associated with eroded sediment (kg ha^{-1})
Eroded Sediment: Annual soil lost in runoff due to erosion (kg ha^{-1})
Soil Total P: Total P content of surface soil (mg kg^{-1}), estimated from soil test P, and clay and organic matter content
P Enrichment Ratio: Unitless ratio of total P in eroded sediment to that in the source soil

APLE estimates dissolved inorganic P loss in runoff (kg ha^{-1}) from soil as:

$$\textit{Dissolved Soil Runoff P} = (\textit{Soil Labile P})\ (0.005)\ (\textit{Annual Runoff})\ (10^{-6}) \qquad [2]$$

Soil Labile P (mg kg^{-1}) is estimated from soil test P. For WI, Labile P is assumed to be one half of Bray-1 soil test P.

In APLE, manure is applied in either a solid or liquid form, and fertilizer in a solid form. APLE assumes that for any manure with solids content less than 15%, 60% of applied manure P infiltrates into soil immediately at application and becomes unavailable for direct loss in runoff. APLE also assumes that the solids from these liquid manures remaining on the soil surface after the initial infiltration cover only 50% of the field area. If tillage occurs, APLE incorporates any applied manure or fertilizer according to user-specified depths of incorporation and percentages of P applied that are incorporated. APLE estimates annual dissolved P loss directly from any manure or fertilizer remaining on the soil surface.

For any manure applied, the model assumes a portion of the manure total P is in a water-extractable P (Shinners et al.) form, which can be analytically measured according to procedures in the APLE documentation. APLE estimates dissolved manure P loss in runoff from this manure WEP on the soil surface. The portion of manure P that is not in a WEP form (non-WEP) at application can mineralize during the year and add to manure WEP on the soil surface. APLE assumes that for winter-applied manure, which APLE simulates as the first season of the year, 20% of non-WEP left on the soil surface after infiltration of liquid P, injection, or tillage mineralizes into WEP. This value is 15% for spring-applied manure, 10% for summer-applied manure, and 5% for fall-applied manure. The user specifies the season of application.

APLE estimates annual manure or fertilizer dissolved P loss in runoff as:

Manure Runoff P = (Manure WEP)(Annual Runoff/Precipitation)(P Distr. Factor)   [3]
Fertilizer Runoff P = (Fertilizer P) (Annual Runoff/Precipitation) (P Distr. Factor)   [4]

The P Distribution Factor is an empirical factor between 0.0 and 1.0 that distributes released P between runoff and infiltration and is calculated as:

Manure: P Distribution Factor = (Runoff/Precipitation) 0.225   [5]
Fertilizer: P Distribution Factor = 0.034 exp [(3.4) (Runoff/Precipitation)]   [6]

The precipitation represents total rain, snow, and irrigation for an entire year. For fall-applied manure, APLE assumes 75% of manure WEP on the soil surface is available for loss in runoff the same year of application and 25% the following year. When applying equation [3] and [4] for liquid manure, APLE reduces the amount of dissolved P loss in runoff by a factor that accounts for the fact that these manures do not cover the entire soil surface and not all of the annual precipitation interacts with them to contribute to runoff P.

APLE validation for pastures

The processes described above for P loss in runoff from soil, manure, and fertilizer have been well validated. For this project, we adapted APLE so it would simulate P loss in runoff from dung applied by grazing cattle. Below, we describe how APLE simulated P loss in runoff from grazing dung and how we validated this new aspect of the model.

In APLE, a user specifies how many dairy or beef cattle graze the field during the year. This adds dung and P to the field and increases the amount of dissolved P loss in runoff. APLE assumes daily dung production and dung total P content for dairy and beef cattle as listed in Table 1. Dung WEP at deposition is 55% of total P, and 75% of dung WEP is available the same year for P loss in runoff and 25% is available the following year. APLE also assumes that 20% of dung non-WEP on the soil surface mineralizes into WEP the same year.

APLE uses Eqs. [3] and [4] to calculate dissolved P loss in runoff from grazing dung. To do this, APLE reduces the amount of dissolved P loss in runoff by a factor that accounts for the fact that dung does not cover the entire soil surface and not all of the annual precipitation interacts with it to contribute to runoff P. In calculating the reduction factor for grazing dung, APLE first assumes that each 250 g of dung (dry weight) covers an area of 659 cm^2 (James et al., 2007) and calculates what percentage of the field area this covers. APLE then calculates the dung reduction factor as:

Reduction Factor = 1.2 x (250 x % cover) / [(250 x % cover) + 73.1)]   [7] where % cover is expressed in a decimal form. Thus, the important new parts of APLE to validate were the assumptions for dung and P production (Table 1) and Eq. [7] to reduce dung P loss in runoff according to the amount of field area covered.

To validate APLE for grazing cattle, we used data from 19 published studies in the literature that monitored P loss in runoff from grazed pastures (Table 2), as well as data from our runoff monitoring at Pioneer Farm. These studies all reported the input information needed for APLE, including size of field; annual stocking rate; soil P concentration; fertilizer applications; soil organic matter and clay content; and annual rain, runoff, and sediment loss. Figure 2 shows an example of the APLE input screen. We entered all required input information into APLE, predicted annual P loss in runoff, and then compared measured and predicted P loss to assess how well APLE simulated P loss from grazed pastures.

Adapting APLE to estimate P loss from exercise lots and barnyards

APLE was not originally developed to estimate P loss from exercise lots and barnyards, which typically have very high stocking rates and manure accumulation. Runoff generation, erosion, and P loss from these areas can be much different than from cropland and pastures. Therefore, a major part of this project was to adapt APLE to estimate P loss from exercise lots and barnyards. This section describes the process we undertook to do that.

The APLE Barnyard model is a simplified version of APLE, requiring input for only soil test P, barnyard or lot area, annual rain and runoff, number of cattle in the lot per day (on average across a year), number of days between lot manure cleanouts, and surface type (paved or earth).

Dissolved P loss

For dissolved P loss, the model requires two variables be known: how much manure P is available for loss in runoff and how much rain interacts with the manure to release that manure P to runoff.

The model first calculates how much total manure is deposited by cattle between cleanings (i.e., mechanical scarping and removal of manure from lot) based on animal numbers and data in Table 1. The model assumes that a maximum of half of the lot area will be covered by manure. This is supported by observations in the literature (Chang and Adriano, 1975); (Miller et al., 2006). As before, the model assumes 250 g of manure (dry weight) covers 659 cm^2 and then calculates how much manure is required to cover half of the lot area. The model then uses the minimum of this half-lot manure or total manure applied between cleanings to determine how much manure is available for dissolved P loss in runoff. The model then determines how much total P is in the available manure based on data in Table 1, and assumes manure WEP is 55% of total P. The model assumes 20% of the remaining 45% non-WEP is mineralized and adds this to the total manure WEP available.

Once available WEP is estimated, the model estimates how much rain will interact with that manure. With infrequent cleanings (once or twice a year), the model uses total annual rain in calculations. For frequent cleanings (weekly), the model assumes only a portion of the annual rain will interact with the manure applied between cleanings. The model calculates this rain portion using the ratio of manure applied between cleanings to the manure that could cover half of the lot area. For paved lots, the model assumes this entire rain portion interacts with manure. For earth lots, the model reduces this rain portion again based on the ratio of actual lot area covered to the maximum coverable area (0.5 of total lot area).

With the manure mass and rain amount known, the model calculates an extraction coefficient (Kw) to determine how much of the available manure WEP is actually lost in runoff. Kw, which ranges from 0 to 1, is calculated as

$$Kw = (1.2 \times W) / [(W) + 73.1)] \qquad [8]$$

where W is a water:manure mass ratio (cm^3/g). The water volume (cm^3) is calculated by multiplying the depth of rain (Vadas et al.) that interacts with manure, as determined above, by the area covered by manure (cm^2). For paved lots, this area is multiplied by a factor of 5. Again, this is an empirical function included for more accurate predictions, but is physically reasonable given that rain from a greater area mixes with manure given the lack of infiltration. The model mulitples Kw by available manure WEP to determine how much dissolved P is lost in runoff. For paved lots, all this manure P is lost in runoff. For earth lots, it is assumed a portion of this manure WEP will infiltrate into soil based on Eqs. [3] ad [5].

Finally, for both paved and earth lots, the model divides the amount of dissolved P lost in runoff by the portion of annual rain used in calculations. This conceptually accounts for the idea that for frequent cleanings, the model is determining the amount of dissolved P lost in the time between cleanings, with the idea that there is always a new, fresh source of P available to be lost from one cleaning to the next. So the model is essentially adding up all the estimated P loss from the time between cleanings.

Particulate P loss

Predicting particulate P loss in runoff requires predicting loss of sediment in runoff and the P content of that sediment. Gilbertson et al. (1972) observed a consistent relationship between the volume of runoff for a storm and the amount of sediment lost (kg/ha) in runoff from feedlots. This suggests that physical surface conditions on a lot remain fairly constant through time so that sediment loss is driven mostly by how much water is moving across the surface. We compiled annual runoff and sediment loss data from several studies in the literature (Coote and Hore, 1979; Edwards et al., 1972; Edwards et al., 1983; Edwards et al., 1986; Gilbertson et al., 1971a; Younos et al., 1998), and developed an equation to predict annual sediment loss from lots (ton/acre) from annual runoff (in) as:

$$\text{Annual sediment loss} = 0.058 \times (\text{annual runoff})^2 + 0.631 \times (\text{annual runoff}) \qquad [9]$$

Based on this empirical relationship, the model predicts sediment loss based on user-input annual runoff.

The next step to predict particulate P loss in runoff was to estimate the P content of the eroded sediment. For paved lots, the only source of eroded solids is manure. Therefore, information in Table 1 is used to estimate the P content of the eroded sediment. For earth lots, this method over-predicted sediment P loss by a factor of three. Because solids loss was not over-predicted, this suggests that the P content of the solids from earth lots was overestimated. This makes sense considering that solids from earth lots will be a mix of both manure and soil. The model thus assumes solids P content is three times less for earth lots. Cramer et al. (1976) measured the P content of solids in settling basins draining a paved and an earth lot in WI. They found that the P content of solids from the paved lot was about three times greater than the P content in solids from the earth lot. This provides justification for reducing the P content of solids from earth lots by a factor of three.

For scraped lots that are consistently cleaned, the method above over-predicted P loss, assumedly because erosion of solids was overestimated. Therefore, the model estimates how much lot area is covered before the lot is cleaned (as a fraction of the maximum lot coverage of 0.5) and uses that as a factor to reduce available manure for loss as solids (e.g., if 23% of a lot is covered in a week, solids loss is reduced by multiplying by 0.23).

To validate APLE for P loss from barnyards and exercise lots, we used data from 12 published studies in the literature that monitored P loss in runoff from such lots (Table 3). We also used unpublished data from a barnyard lot at Pioneer Farm. These studies all reported the input information needed for APLE, including size of lot; animal stocking rate; cleaning frequency, lot surface type, and annual rain, and runoff, and sediment loss. Figure 2 shows an example of the APLE input screen. We entered all required input information into APLE, predicted annual P loss in runoff, and then compared measured and predicted P loss to assess how well APLE simulated P loss from cattle lots.

Grazing farm surveys and sample collection and analysis

We gathered management data from four grazing dairy farms to be able to make assessments of whole-farm P loss using both the APLE model and SNAP+ software. Two farms were located in north-central WI near Athens and Edgar, and the other two farms were located in southeastern WI near Richland Center and Blanchardville (Fig. 2). The farms thus represented differences in soil type and topography that would impact P loss in runoff. Physical and management details of the farm are presented in the Results and Discussion section.

To gather management data from the four farms, we used a questionnaire method to provide snap-shot assessments of cattle, feed, fertilizer, manure, and cropping management. We visited each farm three times, in January, June, and November, 2011 to get information in late fall/winter, spring/early summer, and late summer/fall management. At each visit, questions were designed to provide a snap-shot of management for the period “yesterday-today-tomorrow”, thus focusing on current management to increase the accuracy of information being provided. Compiling information from visits across the major seasons provided information so we could construct modeling scenarios for typical management across a whole year (Powell et al., 2008).

At the first visit in winter, we compiled an overall picture of each farm, including herd size and composition; livestock facilities; cropland acreage, use, and rotations; tillage practices; and feed, fertilizer, and manure management. We then compiled information specific to winter management, such as how many cows were being milked, what and how much was being fed, where animals were located, and what was being done with manure. At the June and November visits, we compiled information specific to management at that time of year, concentrating especially on pasture and grazing management. At each visit, we also collected samples of all feeds currently fed to lactating cows and fecal samples from the same cows. We analyzed the feeds and feces for moisture content and total P at the University of Wisconsin Soil and Plant Analysis Lab.

We investigated the impact of lactating cow diets on fecal P by developing a relationship between cattle feed P content and fecal P content. To do this we estimated an overall P content (dry matter basis) of cow diets by first multiplying the "as fed" mass of each feed ingredient (e.g., grain mix, hay), as determined from producer information during surveys, by the P content of each ingredient. We then divided the sum of the P mass/P content products by the sum of the feed masses to calculate a weighted average P content for the entire diet. We followed this procedure for all lactating cows on all farms for the three farm visits, as well as fecal samples for calves on the fall visit of the Athens farm. We also collected cow fecal P and feed P data from 12 published studies in the literature that investigated the impact of diet on fecal P and compared our farm results with the literature data.

Developing annual management scenarios for SNAP+

Our objective in this part of the project was to use the SNAP+ nutrient management software to estimate runoff and erosion from all areas on the four grazing farms. We would then use this runoff and erosion information as input into APLE to predict whole-farm P loss and estimate the relative contribution of P loss from pastures. To do this, we needed to generate annual simulation scenarios for SNAP+. The following section details the process we followed for these annual simulations.

The first major step in SNAP+ simulations was to determine land use and soil types. In general, we focused on broad land use and soil type categories and not on specific fields. For example, the Richland Center farm has pastures on the "home farm" but uses rented fields on four separate, local farms for crop production. We did not simulate each individual field used by the producer, but instead created land use groups based on survey information that included cropland, lactating cow pastures, heifer and dry cow pastures, over-wintering and exercise lots, and barnyards. Then, we used the NRCS Web Soil Survey to determine the major soil types for each land use. When a certain land use had more than one major soil type, we divided that land use into more than on group. For the Richland Center example, we divided cropland and pastures into several groups based on slope categories of 0-6%, 6-12%, 12-20%, and 20-30%. For each final land use group, we selected in SNAP+ the number of acres based on producer information, soil type, slope, and distance to surface water based on information from the Web Soil Survey. For each land use group in SNAP+, we entered soil property information (pH, organic matter, and soil test P) based on information from soil testing reports provided by producers.

The second major step in the SNAP+ simulations was to determine the amount of manure generated annually on the farm. To do this we used producer information to determine the average number of cows on the farm over the whole year in the categories of lactating cows, dry cows, and heifers. SNAP+ then automatically determined the annual mass of manure generated by each cow category. We verified these estimates when possible using producer information. For the Athens farm as an example, a manure pit is used to store manure generate from lactating cows in the barn. Based on producer information, we estimated an average annual number of lactating cows and how much of their total annual time was spent in the barn. We entered this information into SNAP+ to estimate how much manure would theoretically be stored in the pit. We then compared this estimate to how much manure the producer estimated is removed from the pit each year for land application. In general, we found the SNAP+ manure generation estimates matched producer information well. On the Athens farm for example (see Results and Discussion section for farm description), the producer said he spreads about 2/3 of his annual manure collected on 55 acres of corn land at a rate of 8000 gallons/acre. This equates to about 440,000 gallons spread on corn land and 660,000 gallons of total manure collected annually. The farm has an annual average of 61 lactating cows from which manure is collected. SNAP+ estimates that these cows would produce about 610,000 gallons of manure annually, which matches well with producer information.

The third major step in SNAP+ simulations was to establish crop rotation and manure spreading scenarios for all land use groups. We used producer information to determine the crop rotation for all cropland use groups. For example, the Blanchardville farm has 100 acres of cropland split into three land use groups based on soil types, but all with the same five-year rotation of one year corn silage, one year of alfalfa/oats/grass hay mix, and four years of established alfalfa/grass hay. We also entered tillage practices based on producer information.

For manure spreading practices, we used producer information on amount of time cows spent in different locations and SNAP+ manure quantity estimates to determine the amount of manure applied annually to all land use groups. For example, producers told us how much time lactating cows spend grazing pastures in all seasons. We converted this information into a percent of annual time and thus a percent of total manure generated by all lactating cows and used this estimate as the amount of manure applied to pastures. We followed a similar procedure for all manure applied directly by all cow groups in pastures, over-wintering and exercise lots, and barnyards. For cropland, manure spread came from storage from cattle housing, and manure collected from over-wintering and exercise lots, and barnyards. Again, we used producer information on cow time and SNAP+ annual manure estimates to determine how much manure was collected from these different areas. We then determined cropland manure application rates based on information from producers. On the Edgar farm, for example, there was an annual average of 164 lactating cows that annually generated 3586 tons of manure (dry weight), as estimated by SNAP+. All of the manure collected from the barn and spread onto cropland was from lactating cows. Based on producer information, we estimated that lactating cows spent 35% of their total annual time in the barn (e.g., in barn 23 h per day from December 1 to February 1, complete transition to overwintering lot by April 1, 3 h per day all year in barn for milkings), which is equivalent to 1280 tons. Of this manure, 25% was spread onto hay cropland and 75% onto pastures. We followed a similar procedure to estimate manure application rate for all cropland on all farms.

Estimating whole-farm P loss with APLE and SNAP+

We followed these three major steps to complete annual management scenarios for all four farms. We then used SNAP+ to automatically run the WI P Index to estimate P loss in runoff from all land use groups on all farms. These land use groups included cropland, pastures, over-wintering and exercise lots, and barnyards. We then took field erosion and runoff estimates from SNAP+ as inputs for APLE and used APLE and the annual management scenarios to estimate P loss from all farm areas. We then compared APLE and WI P Index results.

Results and Discussion

Runoff monitoring at Pioneer Farm

We monitored 20 runoff events between August 2010 and May 2012. These events generated 118 runoff samples, meaning that not all eight basins had runoff for all events. Five events and 33 samples were caused by rain outside of the winter period, and 15 events and 85 samples were due to snowmelt. Although runoff is clearly weather dependent, it is likely that most runoff from pastures in WI will occur in winter and late spring from snowmelt, while much less will occur from rainfall outside of this period.

In the 118 runoff samples, sediment concentrations were consistently very low, averaging only 0.20 g/L, with a maximum of only 1.6 g/L. Total P concentrations ranged from 0.5 to 5.2 mg/L, with dissolved P averaging about 80% of total P in the snowmelt samples and 60% in the rain-runoff samples. These P results are consistent with data in the literature on the magnitude of P concentrations from grazing areas and the relative amount of sediment and dissolved P in runoff.

Based on measured runoff volume and sediment and P concentration data from all events, we estimated annual runoff, erosion, and P loss from the Pioneer farm pastures. Annual runoff for the 12-month period from August 2010 to August 2011 was 2.6 inches, compared to annual rainfall of about 28 inches. Therefore, annual runoff may be about 10% of annual runoff. Annual erosion was very low, at only 0.028 ton/acre. Annual P loss was also low, at only 1.21 lb TP/acre and 1.03 lb DRP/acre. In general, these results show that annual runoff, erosion, and P loss from typical cattle grazed pastures in WI are likely fairly low, and not likely to have a substantial impact on local water quality. However, management practices that increase runoff, erosion, and P loss, such as significantly greater cattle stocking rates or excessive P fertilization, would increase the risk of environmental impact.

Validation of APLE for P loss from pastures and lots

To validate APLE for grazing cattle, we used data from 19 published studies in the literature that monitored annual P loss in runoff from grazed pastures (Table 2). The data represented a variety of cattle types, field areas, and location and associated climate. This variety provided a robust test to see if APLE could accurately predict annual P loss in runoff from pastures.

Figure 4 shows the relationship between measured and predicted, annual total and dissolved P loss in runoff from cattle pastures. Results show APLE was able to reliably predict annual P loss in runoff. The slope and intercept of both regression lines relating measured and predicted values were not significantly ($P < 0.05$) different from one or zero, respectively. The model predicted the measured total P data with an efficiency of 0.98 and the dissolved P data with an efficiency of 0.89 (Nash and Sutcliffe, 1970). Nash-Sutcliffe efficiencies can range from $-\infty$ to 1. An efficiency of 1 corresponds to a perfect match of modeled and observed data. An efficiency of zero indicates that model predictions are as accurate as the mean of observed data, and an efficiency less than zero occurs when the observed mean is a better predictor than the model.

The important new parts of APLE to validate for pasture P runoff were the assumptions for dung and P production (Table 1) and Eq. [7] to reduce dung P loss in runoff according to the amount of field area covered. Results suggest that these two parts of the model provided reliable predictions of pasture P runoff. In fact, without the dung area reduction factor, which would ultimately treat grazing dung the same as machine-applied manure, P loss predictions would be about 50% greater than measured data. This demonstrates the importance of simulating grazing dung different from machine-applied manure.

One benefit of the APLE model is that it gives information on the sources of total P loss in runoff from pastures, including fertilizer, dung, soil, and eroded sediment. The relative importance of each source will of course depend on pasture management, but on average across the entire data set from Table 2, the relative contribution to total P loss was about equal for all four P sources.

To validate APLE for P loss from barnyards and exercise lots, we used data from 12 published studies, plus unpublished data from the Pioneer Farm (Table 3). The data represented a range of cattle types, lot areas and surface types, and locations and associated climates. This range provided a robust test to see if APLE could accurately predict annual P loss in runoff from cattle lots.

Figure 5 shows the relationship between measured and predicted, annual total and dissolved P loss in runoff from cattle lots. Results show APLE was able to reliably predict annual P loss in runoff. The slope and intercept of the regression line relating measured and predicted total P values were not significantly ($P < 0.05$) different from unity or zero, respectively. The model predicted the measured total P data with an efficiency of 0.81. Conversely, the slope and intercept of the regression line relating measured and predicted dissolved P values were significantly ($P < 0.05$) different from unity and zero, with the model under-predicting dissolved P loss. However, given that the model predicted the measured dissolved P data with an efficiency of 0.85 and that there were only 12 data points, results show that dissolved P predictions were still fairly accurate. This is especially true considering that the model results show that dissolved P averaged only about 30% of total P in runoff. Therefore, the degree of under-prediction of dissolved P is likely not enough to affect the reliability of total P loss predictions.

Overall, these model validation results give confidence that APLE can reliably predict dissolved and total P loss from pasture, exercise lots, and barnyards on dairy farms. Since APLE has already been validated to predict P loss from cropland (Vadas et al., 2009), the model can be used to reliably estimate whole-farm, annual P loss from dairy farms.

Relating feed P to cow fecal P on grazing farms

The next section of this report describes the characteristics and management of the four grazing farms. This section simply presents data collected on those farms that relate feed P and fecal P contents. Table 5 lists the feed ingredients, amounts fed, and total P content of lactating cow diets for the four grazing farms in each of three seasons, as well as information for a calf diet from the Athens farm in the fall. Table 5 also lists the weighted average P content of each entire diet. These data show that whole diet total P content ranged from 0.27 to 0.40%, with an average of 0.34%. The P requirement of most lactating dairy cows can be met if the diet contains 0.32-0.38 % P **(NRC, 2001)**. Holstein cows producing milk containing 3.5 percent fat and 3.0 percent true protein have a dietary requirement (dry matter basis) of 0.32, 0.35, 0.36 and 0.38 percent P for milk production amounts of 55, 75, 100, and 120 lbs/day, respectively. The data from the four grazing farms show that most dietary P contents fell within the recommended range.

Figure 6 shows that relationship between cow dietary P and fecal total P content. Data from the 12 literature studies show that there is generally a strong, consistent relationship between diet and fecal P, although there can be variability in these types of data. Dietary P in excess of 0.38% (3.8 g/kg) represents excess P that cannot be used by cows and is excreted in feces. After land-application of manure, this excess P represents an increased risk of P loss in runoff that could be avoided by reducing dietary P. Figure 6 shows that dietary P for the four grazing farms generally fell within the lower range of data collected from the literature, which included measurements from commercial dairy farms. This shows that the grazing producers are generally not over-feeding P, although a few diet P data points are greater than 0.38%. This likely represents the impact of efforts over the past 10 years to better inform dairy producers about cattle diet P requirements and the environmental risks of over-feeding P.

Finally, Figure 6 also shows that data from the four grazing farms agreed well with trends from published literature data. This demonstrates that our methods of farmer surveys accompanied with physical sampling can reliably portray actual farm management. For example, there was much less variability in the diet P/fecal P relationship for data from the Athens and Edgar farms ($r^2 = 0.97$) compared to data from the Blanchardville and Richland Center farms ($r^2 = 0.19$). This degree of variability generally reflects more uncertainty during producer surveys about how much of some diet ingredients were being fed and the ability to take representative samples of those ingredients. This in turn could lead to producers being less able to effectively manage P in diets, and therefore manure.

Simulating whole-farm P loss from WI grazing farms

It is important to emphasize that the P loss data discussed in this section are estimates from the APLE model. Although the model has been well validated to show it reliably predicts P loss from all areas on a dairy farm, the estimates still have some uncertainty. Furthermore, these are estimates of edge-of-field P loss, which represents P that reaches the edge of the field and not necessarily the nearest stream or other water body. It is likely that some portion of the P lost from fields will be retained in natural riparian areas between fields and water bodies.

Jokela and Casler (2011) measured erosion and P loss in runoff from four corn silage fields receiving fall manure application and fall and spring tillage in central WI close to the Athens and Edgar farms. Annual total P loss in runoff was 3.7, 2.8, 1.5, and 3.4 lb/acre for the fields. We simulated the conditions of that study in APLE, using measured runoff and erosion as input, and predicted respective total P loss values of 3.1, 2.4, 1.2, and 3.1 lb/acre. These predictions agree well with measured P loss and demonstrate that APLE is able to reliably estimate P loss in runoff for the farm conditions of the four WI farms. In the same study, measured annual erosion and runoff averaged 2.6 ton/acre and 4.9 inches across the four fields. For the Athens farm that also had corn silage production on similar soil types (see farm details in the next section), the WI P Index estimated annual erosion and runoff at 4.1 ton/acre and 5.0 inches (Table 4). Less erosion in the Jokela and Calser (2011) study is likely due to milder slopes (2% vs 4% simulated for the Athens farm).

Table 4 also shows that annual simulated runoff and erosion from cow pastures on the four grazing farms averages 2.6 inches and 0.13 ton/acre, respectively. Measured annual runoff and erosion from pastures on the Pioneer farm were 2.6 inches and 0.03 ton/acre, respectively. Measured annual total P loss from pastures was 1.21 lb P/acre, while simulated annual total P loss averaged 0.5 lb P/acre. Overall the generally good agreement between measured runoff and erosion and WI P Index and APLE estimates demonstrate that the models can reliably estimate runoff, erosion, and P loss for the four farm conditions encountered in this project.

Blanchardville

The Blanchardville farm (Figure 7) has an annual average of 40 lactating cows, 20 heifers, and 1-2 dry cows. The farm has 100 acres of cropland, with 20 acres of corn silage and 80 acres of a grass/alfalfa hay mix. The cropland is all used in a 6-year rotation with one year of corn silage, one year of an oats/grass/alfalfa seeding mix, and four years of the alfalfa/grass hay mix. Tillage includes chisel plow and disking before corn is planted, and disking after corn going into the hay-seeding year. The farm has 44 acres of rotated pasture for lactating cows and 28 acres of non-rotated pasture for dry cows and heifers. There are also two outdoor lots of 0.5 and 1.0 acre used for over-wintering cows.

Soils on the farm are mostly Sogn silt loams at 2-12% slopes and 12 to 30% slopes (30% of area), Dodgeville silt loams at 6-12% slopes (30% of area), and Dunbarton silt loams at 12-20% slopes (15% of area). The rest of the soils are various silt loams at 6-12% and 12-20% slopes. Thus the farm has fairly steep slopes with soils classified as moderately eroded.

During the year, lactating cows are milked twice per day, spending 2.5 h of daily time in the tie-stall barn, where they are milked in place. These cows are in the barn about 20 h per day and out on the 0.5 acre lot 4 h per day from mid-November until the end of February. Between the beginning of March until mid-April, lactating cows increase their daily time on the lot until they are there all day (except for milkings) by mid-April. From mid-April to mid-May, cows graze the 44 acres of pasture. After that until mid-November, cows will rotate between pastures and hay ground, Overall, lactating cows spend about 45 days on pasture and 148 days on hay ground. Heifers and dry cows are on pasture 24 h per day from mid-April to mid-November, with the rest of their time spent on the 1.0 acre lot.

There is no manure storage on the farm. Based on the above annual cow time and space distribution scenario, we estimated that 104 tons of manure is deposited by lactating cows on the 0.5 acre lot. Of this, about 80% is collected and spread on the corn ground in the fall at a rate of 4.1 tons/acre. We estimated that 334 tons of manure from lactating cows is collected in the barn, of which 267 tons is spread on a daily-haul basis on corn ground (mostly in winter) at an annual rate of 13.3 tons/acre and 67 tons is spread on lactating cow pastures at an annual rate of 1.5 tons/acre. From grazing lactating cows, 114 tons of manure is deposited directly on pastures at an annual rate of 2.6 tons/acre, and 375 tons on hay ground at an annual rate of 4.7 tons/acre. From grazing heifers and dry cows, 136 tons is deposited on pastures at an annual rate of 4.8 tons/acre. One hundred and one tons is deposited in the 1.0 acre over-wintering lot, of which 81 tons (80%) is collected and spread on corn ground in the fall at an annual rate of 4.0 tons/acre.

Table 4 shows APLE simulation results of P loss in runoff from specific land uses and the whole farm for the Blanchardville Farm. Cropland that had tillage (corn silage and hay seeding year) had the greatest erosion and thus the greatest total P loss. Total P loss from these areas with exposed soils was about 50% of total, whole-farm P loss. Erosion and total P loss from pastures and established hay ground was very low, but these areas still represented about 30% of whole-farm P loss because they were the dominant land use. Total P loss from the two over-wintering lots was an order of magnitude greater than the other land uses and amounted to 20% of whole-farm P loss even though these lots were less than 1% of the total farm area.

Richland Center

The Richland Center farm (Figures 8-10) has an annual average of 118 lactating cows, 92 heifers, 23 dry cows, and 20 beef steers. The farm has 200 acres of cropland, all of which are rented locally, with 80 acres of corn silage and 120 acres of a grass/alfalfa hay mix. The cropland is all used in a 5-year rotation with two years of corn silage, one year of an oats/grass/alfalfa seeding mix, and two years of the alfalfa/grass hay mix. All cropland is in no-till management. The home farm has 107 acres of rotated pasture for lactating cows, and 100 acres of non-rotated pasture are rented locally for dry cows, heifers, and steers. There is one 0.25 acre barnyard, and 2.5 acres of lots on the home-farm used for over-wintering and young stock throughout the year.

Soils on the home-farm are mostly Valton, Lamoille, Fivepoints, and Basco silt loams, with most slopes at 6-12% and 12 to 20%. On the rented farms, the dominant soils are Churchtown, Orion, Norden, Valton, and Brownchurch silt loams, with the dominant slopes at 6-12%, 12 to 20%, and 20-30%. The rest of the soils on the home and rented farms are various silt loams at 6-30% slopes. Thus the farms have fairly steep slopes with most soils classified as moderately eroded.

During the year, lactating cows are milked twice per day, spending 5 h of total time in the parlor, free-stall barn, and connected barnyard. These cows are in the barn and barnyard 24 h per day from November 1 to May 1. The rest of the year, they are rotated through the 107 acres of home-farm pastures. All heifers, dry cows, and steers are housed predominately on the 2.5 acres of lots on the home-farm from November 1 to May 1. Some heifers are in the barnyard during this period, and some move onto part of an adjacent pasture between March 1 and May 1. Between May and November, most heifers, dry cows, and steers are on non-rotated rented pastures 24 h per day. Some of the youngest heifers remain on lots on the home farm during this period.

There is a small pit on the home farm that stores manure from the parlor, barn, and half of the barnyard. Based on the above annual cow time and space distribution scenario, we estimated that 1231 tons of manure are collected in the pit and uniformly distributed onto all corn ground in spring (80%) and fall (20%) at an annual rate of 15.4 tons/acre. About 490 tons of manure are deposited in the part of the barnyard where manure is not collected in the pit. Of this, 85% is spread on corn ground at an annual rate of 5.2 ton/acre. On all the winter and young stock lots on the home-farm, 885 tons of manure is deposited, of which 35% is collected and spread on corn ground at annual rate of 3.9 tons/acre. From grazing lactating cows, 1090 tons of manure is deposited on pastures at an annual rate of 9.9 tons/acre. From grazing heifers, dry cows, and steers, 771 tons is deposited on pastures at an annual rate of 7.7 tons/acre.

Table 4 shows APLE simulations results of P loss in runoff from specific land uses and the whole farm for the Richland Center Farm. Cropland that had exposed soils, even with no-till management (corn silage and hay seeding year), had the greatest erosion and thus the greatest total P loss. Total P loss from these areas with exposed soils was 40% of total, whole-farm P loss. Erosion and total P loss from pastures and hay ground was very low and represented about 22% of whole-farm P loss. Total P loss from the over-wintering and young stock lots and the barnyard was one to two orders of magnitude greater than the pasture and cropland other land uses. This P loss combined amounted to 36% of whole-farm P loss even though these areas were only 1% of the total farm area.

Edgar

The Edgar farm (Figures 11-12) has an annual average of 164 lactating cows, 130 heifers, and 17 dry cows. The home farm has 226 acres of pasture, along with 70 acres of locally rented grass hay ground. Cows are overwintered on a several acre portion of pasture, with a new area used every year. There is a 2-acre dry lot next to the barn used for freshening cows and infrequently for lactating cows in the barn in the winter.

Soils on the home-farm and rented hay ground are all Loyal, Marshfield, and Withee silt loams, with slopes at 0-3% and 1 to 6%. Thus the farms have mild slopes that are not prone to erosion.

During the year, lactating cows are milked twice per day, spending 3 h of total time in the parlor, free-stall barn, and connected barnyard. These cows are in the barn and barnyard 23 h per day from December 1 to February 1, with 1 h spent on the dry lot. These cows gradually dry off and are moved onto over-wintering lots until April 1, when there are no cows in the barn. From April 1 to December 1, lactating cows graze pastures, with some time spent in the barn on hot days. The 17 dry cows spend 12 h per day in the barn from April 1 to June 1, are on pasture all other times between April 1 and December 1, and are on a wintering lot from December 1 to April 1. Heifers are also on a wintering lot from December 1 to April 1, and on pasture 24 h per day for the rest of the year.

There is a pit on the home farm that stores manure from the parlor, barn, and barnyard. Based on the above annual cow time and space distribution scenario, we estimated that 1280 tons of manure are collected in the pit, of which 25% is spread onto rented hay ground at an annual rate of 4.5 tons/acre and 75% is spread on pastures at a rate of either 3.7 tons/acre (north fields) or 2.1 tons/acre (south fields). We estimated that 36 tons of manure is deposited on the 2-acre dry lot, 576 tons on the 10-acre overwintering lot for dry cows and older heifers, and 250 tons on the 18-acre overwintering lot for young heifers. Finally, 3259 tons of manure are deposited across all pastures at an annual rate of 14.4 tons/acre.

Table 4 shows APLE simulation results of P loss in runoff from specific land uses and the whole farm for the Edgar Farm. Because there is not tilled or exposed soil on the farm, erosion and total P loss are generally very low, except for some P loss from the winter pasture, and significant P loss from the dry lot. For the whole-farm, P loss from pastures and hay fields represented 43% of whole-farm loss, while P loss from the winter pastures and dry lot was 57% percent, even though these areas represented only about 10% of the total land area.

Athens

The Athens farm (Figures 13-14) has an annual average of 60 lactating cows, 46 heifers and 21 calves, and 9 dry cows. The farm has 110 acres of cropland, with 30 acres of corn silage, 30 acres of corn for grain, and 50 acres of a grass/alfalfa hay mix. The cropland is all used in a 6-year rotation with three years of corn, one year of an grass/alfalfa seeding mix, and two years of the alfalfa/grass hay mix. The home farm has 70 acres of rotated pasture for lactating cows, and 30 acres of non-rotated pasture dry cows, heifers, and calves. There is also a 70 acre wooded area near the cropland for heifer grazing. There is one 0.2 acre barnyard, and one 0.5 acre dry lot on the home-farm for cows and heifers.

Soils on the home farm and cropland are all Loyal, Marshfield, and Withee silt loams, with slopes at 0-3% and 1 to 6%. Thus the farms have mild slopes that are not prone to erosion.

During the year, lactating cows are milked twice per day, spending 2.5 h of total time in the parlor, tie-stall barn, and connected barnyard. These cows are in the barn and barnyard 22 h per day from November 1 to May 1, with 2 h spent in the barnyard. From May 1 to November 1, lactating cows graze pastures. Dry cows are the barn from November 1 to May 1, with some time spent in the barnyard, and are on pasture all other times between May 1 and November 1. Twenty-two of the heifers are in the barnyard from November 1 to May 1, and are on pasture all other times between May 1 and November 1. The rest of the heifers are off the farm in the winter and on pasture the rest of the year. The calves spend six months on the dry lot and 6 months on pasture.

There is a manure pit on the home farm that stores manure from the parlor and barn. Based on the above annual cow time and space distribution scenario, we estimated that 776 tons of manure are collected in the pit, with 67% spread onto corn ground at an annual rate of 9.4 tons/acre and 33% spread on lactating cow pastures at a rate of either 3.7 tons/acre. We estimated that 210 tons of manure goes into the barnyard, of which 90% is collected and spread on lactating cow pastures in summer at a rate of 3.0 tons/acre. Thirty-two tons of manure goes into the calf dry lot, of which 80% is spread on the same pastures in summer at a rate of 0.5 tons/acre. Grazing lactating cows deposit 598 tons of manure onto pastures at a rate of 8.5 tons/acre. Manure from grazing heifers and calves is deposited in six different pasture locations, at rates ranging from 1.6 tons/acre to 20 tons/acre.

Table 4 shows APLE simulation results of P loss in runoff from specific land uses and the whole farm for the Athens farm. Cropland with exposed soils (corn and hay seeding year) had the greatest erosion and thus the greatest total P loss. Total P loss from these areas with exposed soils was about 65% of total, whole-farm P loss. Erosion and total P loss from pastures and hay ground was very low and represented about 25% of whole-farm P loss. Total P loss from the calf lot and the barnyard was one to two orders of magnitude greater than the pasture and cropland other land uses. This P loss combined amounted to only 10% of whole-farm P loss, mostly because they were only 0.2% of the total farm area.

Summary of APLE farm simulations

In general, whole-farm P loss per unit land area from the four grazing farms was relatively low (Table 4). Phosphorus loss from pastures and hay land was consistently very low. This demonstrates that these types of grazing farms as whole may not represent significant sources of P loss to the environment. However, some land uses on these farms have the potential for significant P loss.

Results in Table 4 show that the P loss per unit land area from barnyards, dry lots, and over-wintering areas can be very high. This is expected given that these areas have very high manure loading rates due to high animal densities. Furthermore, these areas represent from about 10% to almost 60% of total farm P loss, depending on lot management and P loss from other farm land uses. These areas serve an important cattle housing function during winter and for young stock on grazing farms. However, they can represent a significant source of whole-farm P loss that should receive management attention. For example, our APLE simulations suggest that frequent cleaning of barnyards can greatly reduce P loss. Containing runoff in a storage area can also help reduce P loss and possibly capture nutrient for agronomic use on the farm. The Dairy Forage Research Center and the UW-Madison and Platteville are currently collaborating on research to monitor and model P loss from barnyards and cattle lots.

Simulation results (Table 4) also show that P loss can be quite high from corn land and hay land in a seeding year, mostly due to increased risk of soil erosion and sediment P loss. Corn and hay are produced on these farms as cattle feed, so these land uses are required. However, they should be managed to reduce P loss. For example, the Edgar farm has all permanent hay land, which greatly reduces whole-farm P loss in erosion. However, they are required to purchase supplemental corn silage and grains for feed. Although we did not quantify this practice in this project, this land and feed management likely results in greater net import of P on to the farm compared to other farms. A greater net import likely results in greater accumulation of P in soil through time as manure is recycled through land application. This scenario is evident in soil P concentrations on the Edgar farm, which were the greatest of any farm. Another management practice to reduce sediment P loss is no-till. For example, the Richland Center and Blanchardville farms both had steep slopes and erodible soils. However, The Richland Center farm had less whole-farm P loss per acre because of no-till management.

One benefit of the APLE model is that it gives information on the source and form of P loss in runoff. In general, there were no consistent trends in the dominant source (i.e., cropland or cattle lots) or form of P loss (i.e., dissolved or sediment P) for specific land uses across all farms. For example, P loss from eroded sediment averaged 40% of total P loss from corn land on the Richland Center farm, but 93% on the Athens farm. Rather, the source of P loss depended on farm characteristics and management. APLE simulation results in Figure 15 for all areas except barnyards and cattle lots show that P loss from eroded sediment dominated at high rates of total P loss. At lower rates of total P loss, soluble P loss from soil and manure contributed more to total P loss, but mostly due to less erosion and sediment P loss instead of greater soluble P loss. In general, simulation results show the greatest variability in P loss was due to erosion and sediment P loss. When erosion was low, total P loss was also low. Sediment P loss also dominated total P loss from barnyards and cattle lots, ranging from 75 to 95% on all farms expect the barnyard on the Athens farm (sediment P loss at 43%) that was cleaned weekly.

Comparing APLE and WI P Index simulation results

Both APLE and the WI P Index, which is part of the SNAP+ nutrient management software, estimate P loss in runoff. Both models use a similar approach to simulate total P loss in runoff as the sum of particulate P loss in eroded sediments and dissolved P loss from soils, manures, and fertilizers. Both models were developed in conjunction with each other and thus share some of the same equations. However, because the P Index was developed specifically for WI conditions and APLE was developed to be used nationally, there are some important differences in how the models simulate P loss. In this project, we wanted to focus on dissolved P loss from grazing dung to see if our results could help improve P Index simulations for grazed pastures. We also discuss some other differences in the models that were a source of different P loss estimates.

Simulating total P loss

In both APLE and the WI P Index, total P loss in runoff is the sum of particulate P loss in eroded sediments and dissolved P loss from soils, manures, and fertilizers. Results in Figure 16 show that simulated total P loss from all areas on all farms except lots and barnyards was similar for both models. This is a reflection of the similarities in approaches and equations that the two models use to estimate P loss.

There were two circumstances when the P index estimated greater P loss than APLE (Fig. 16). The first was for the Blanchardville farm where manure was winter applied to corn land due to lack of storage. In these situations, the WI P Index predict much more dissolved P loss from manure on the surface. Both models use the same equations to estimate this dissolved P loss. These equations use the ratio of runoff/precipitation so that as the ratio increases, the estimated dissolved P loss also increases. APLE uses an annual runoff/precipitation ratio, whereas the P Index uses seasonal ratios. In the P Index, a relatively high winter ratio combined with winter manure application results in greater estimates of dissolved P loss.

The second circumstance where the P Index estimated greater P loss was for the Richland Center farm where manure was applied to corn ground. In this situation, the models estimated similar P loss for low slopes when erosion was fairly low (0.5 and 1.4 tons/acre). However, when erosion was much greater (2.8 and 4.0 tons/acre), the P index estimated much greater particulate P loss. This is due to differences in how the models estimate the impact of manure applications on soil total P concentrations, which in turn determine the P content of eroded soil. The P Index generally increases soil total P more than APLE for a given amount of applied manure P, thus leading to greater estimates of particulate P loss.

Simulating particulate P loss

There was a very good relationship between APLE and P Index particulate P loss (APLE = 0.96 x (P Index) -0.11; $r^2 = 0.95$). This reflects the fact that APLE used the same estimates for erosion as the P Index, but also the close similarities in equations used to estimate soil total P and thus particulate P loss. One notable exception is described in the previous section for manure application to corn ground with relatively high rates of erosion.

Simulating dissolved P loss

In both APLE and the P Index, both soil and manure on the surface were sources of dissolved P loss in runoff. Both models estimate dissolved P loss from soil by multiplying soil test P content by an extraction coefficient. Figure 17 shows that the P Index-predicted dissolved P loss was much greater than APLE-predicted P loss for soils from the Blancardville and Richland Center farms and only slightly less than APLE P loss for soils from the Edgar and Athens farms. These differences are due to differences in extraction coefficients used for different sol types in the models. APLE uses a constant 0.0025 coefficient, while the WI P Index uses coefficients of 0.002 or 0.006 depending on soil type.

For dissolved P loss from manures on the soil surface, there was generally a good correlation between APLE and P Index predictions (Fig. 18). The notable exception was for manure applied to cropland in winter, which is discussed in the section above. For pastures and grazed hay land, estimated manure dissolved P loss was about 60% greater for the P Index than for APLE. This is primarily because APLE considers that grazing manure does not cover the entire field area, which reduces the amount of manure P available for loss in runoff. The APLE validation section in this report suggests that this field area coverage is an important assumption to make when simulating dissolved P loss from grazed pastures. For cropland receiving manure outside of the winter period, the P Index generally estimated about 50% less dissolved P loss than APLE. This is in part because the P Index estimated 40% of total dairy manure P applied is in a water-extractable form available to loss in runoff. APLE uses a value of 50%. The other reason is because the P Index uses seasonal runoff/rain ratios to estimate manure dissolved P loss and APLE uses a single, annual ratio. The seasonal ratios in the P Index (excerpt for the winter season) are less then the annul ratio used in APLE, which leads to less manure dissolved P loss in runoff.

Project Conclusions

Our project has a number of conclusions that have potentially important management and policy implications.

1. The project has established a data set for P loss in runoff from dairy and beef grazed pastures for WI conditions. It has also increased the research capacity for future evaluation of grazing practices on nutrient loss in runoff. Both of these factors have increased the ability to develop reliable models for estimating the environmental impact of cattle grazing, especially as related to other dairy production systems. Specifically, the project has provided important data for evaluating APLE's ability to predict annual P loss from grazed pastures and also for eventually updating the WI P Index for grazing situations. Finally, the project served as an impetus for developing and evaluating a revised APLE model for P loss from cattle barnyards and feedlots.

2. Results from the project demonstrate that we can use the APLE model to reliably estimate P loss in runoff from all areas on a dairy farm. However, such predictions require reliable estimates of runoff and erosion as input into APLE. Given these, APLE can be used to identify areas on dairy farms of greatest P loss and thus in need for alternative management to reduce that P loss. This is important because WI is likely

unique in the U.S. in its development of models like APLE and the WI P Index to achieve quantitative assessment of whole-farm P loss.

3. The project builds on previous research to show that our producer survey methods can rapidly provide reliable management information to assess whole-farm P loss.

4. In general, runoff monitoring and modeling results show that at the whole-farm level, average P loss (lb/acre) from these types of farms is generally low, especially from grazed pastures. This generally reflects the low rates of erosion from grazing farms where a significant portion of land is in permanently vegetated pastures or hay, or has hay in rotation with low soil exposure. However, there are areas on grazing farms that represent sources of significant P loss. For cropland, the greatest P loss was from areas with exposed soil, typically for corn production, and especially on steeper sloping land. The farm areas with the greatest P loss had concentrated animal housing, including barnyards, and over-wintering and young stock lots. These areas can represent from about 10% to almost 60% of total farm P loss, depending on lot management and P loss from other land uses.

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Table 1. Daily feces production and fecal total P content for grazing dairy and beef cattle.

Animal Type	Daily Fecal Production (kg)	Fecal Total P content (kg/kg)
Lactating Dairy Cow	8.9	0.0088
Dairy Heifer	3.7	0.0054
Dairy Dry Cow	4.9	0.0061
Dairy Calf	1.4	0.0054
Beef Cow	6.6	0.0067
Beef Calf	2.7	0.0092

Table 2. Details of 19 studies used to validate APLE for P loss in runoff from cattle-grazed pastures.

Reference	Location	Duration	Field Area	Cattle Type	P Forms Measured
		months	ha		
(Capece et al., 2007)	Florida	72	20.2-32.4	beef	DRP
(Cournane et al., 2011)	New Zealand	25	1.3	beef	TP, DRP
(Edwards et al., 1996)	Arkansas	24	1.2	beef	DRP
(Fleming and Cox, 1998)	Australia	12	2.4	dairy	DRP
(Harmel et al., 2009)	Texas	84	1.2	beef	TP, DRP
(Holz, 2010)	Tasmania	36	12.1	dairy	TP, DRP
(Kurz et al., 2006)	Ireland	16	0.5-1.5	beef	DRP
(Lambert et al., 1985)	New Zealand	36	0.1-1.5	sheep	TP
(Mapfumo et al., 2002)	Canada	36	2.2	beef	DRP
(McDowell et al., 2003)	New Zealand	6	3.0	dary	TP, DRP
(Melland et al., 2008)	Australia	30	0.5	sheep	TP
(Menzel et al., 1978)	Oklahoma	120	11.0	beef	TP, DRP
(Olness et al., 1975)	Oklahoma	12	9.6-11.0	beef	TP, DRP
(O'reagain et al., 2005)	Australia	12	1.0	beef	TP
(Owens and Shipitalo, 2006)	Ohio	120	17.2	beef	DRP
(Schepers and Francis, 1982)	Nebraska	36	32.5	beef	TP, DRP
(Smith, 1987)	New Zealand	20	16	sheep	TP, DRP
(Smith and Monaghan, 2003)	Australia	0.09	10	beef, dairy	DRP
(Vankeuren et al., 1979)	Ohio	24	17.2	beef	TP

Table 3. Details of 12 studies, plus data from UW Platteville Pioneer Farm, used to validate APLE for P loss in runoff from cattle barnyards and exercise lots.

Reference	Location	Duration	Lot Area	Cattle Type	Lot Type	P Forms Measured
		months	ha			
(Coote and Hore, 1979)	Canada		0.05-0.24	Beef, dairy	earth, paved	TP
(Cramer et al., 1976)	WI	24	0.24-2.1	dairy	earth, paved	TP
(Edwards et al., 1972)	OH	36	0.17	beef	earth	DRP
(Edwards et al., 1983)	OH	36	0.024	beef	earth	TP
(Edwards et al., 1986)	OH	36	0.024	beef	paved	TP
(Gilbertson et al., 1971b)	NE	12	0.2	beef	earth	TP
(McVay et al., 2004)	GA	24	0.08	dairy	earth	DRP
(Miller et al., 2004)	Canada	60	0.5	beef	earth	TP, DRP
(Pinkowski et al., 1985)	IL	48	0.5	beef	paved	TP
(Uusi-Kamppa et al., 2007)	Finland	24	1.0	beef	earth	DRP
(Westerman and Overcash, 1980)	NC	24	1.37	dairy	earth	TP
(Younos et al., 1998)	VA	6	0.58	dairy	earth	TP
Pioneer Farm	WI	24	0.15	dairy	paved	TP, DRP

Table 4. Details of APLE-simulated total P loss from the four WI grazing dairy farms.

Land Use	Acres	Runoff (in)	Erosion (ton/acre)	Total P Loss (lb/ac)	Total P Loss (lb)	Total P Loss (% of Total Farm Loss)
			Blanchardville			
Corn silage	16.7	3.0	4.2	4.9	82.3	22.0
Hay - seed year	16.7	3.9	5.4	6.1	101.4	27.1
Hay established	66.8	3.2	0.6	1.0	66.1	17.7
Cow pastures	72.0	2.5	0.4	0.7	49.1	13.1
Cattle lots	1.5	8.0	8.8	50.2	75.3	20.1
Whole Farm				*2.4*		
			Richland Center			
Corn silage	80.0	2.7	1.2	1.8	142.0	21.2
Hay - seed year	40.0	3.3	3.5	3.2	129.3	19.3
Hay established	80.0	2.7	0.3	0.3	27.6	4.1
Young pasture	100.0	2.9	0.9	0.8	84.4	12.6
Cow pasture	121.5	2.4	0.1	0.3	40.1	6.0
Cattle lots	2.8	8.0	8.8	42.0	115.5	17.3
Barnyard	0.3	15.0	22.6	520.2	130.0	19.4
Whole Farm				*1.6*		
			Edgar			
Hay established	70.0	2.8	0.0	0.2	16.6	5.6
Cow pasture	226.0	2.9	0.0	0.5	111.1	37.3
Winter pasture	28.0	3.5	0.1	2.2	61.6	20.7
Cattle lot	2.0	8.0	8.8	54.1	108.2	36.4
Whole Farm				*1.2*		
			Athens			
Corn grain	30.0	4.0	1.7	2.7	79.8	17.9
Corn silage	30.0	5.0	4.1	5.5	164.0	36.8
Hay - seed year	16.7	4.9	2.0	3.0	49.2	11.1
Hay established	33.3	4.0	0.4	0.8	27.9	6.3
Cow pasture	70.0	2.7	0.0	0.5	34.8	7.8
Young pastures	99.0	3.7	0.2	0.5	48.5	10.9
Cattle lots	0.5	8.0	8.8	41.7	20.9	4.7
Barnyard	0.2	15.0	22.6	102.5	20.5	4.6
Whole Farm				*1.6*		

Table 5. Feed ingredients, amounts fed, and total P content for lactating cow and calf diets for the four grazing farms.

Feed Ingredient	Amount Fed	Total P	Amount Fed	Total P	Amount Fed	Total P
	Dry lb/cow/d	% Dry Matter	Dry lb/cow/d	% Dry Matter	Dry lb/cow/d	% Dry Matter
	Winter		Spring		Fall	
			Blanchardville			
Hay	14.0	0.37	--	--	--	--
Grain mix	5.7	0.30	7.9	0.31	7.5	0.41
Corn silage	8.1	0.19	--	--	--	--
Mineral mix	0.1	0.3	--	--	--	--
Pasture[1]	--	--	20.0	0.26	20.0	0.25
Whole diet		*0.31*		*0.27*		*0.29*
			Richland Center			
Haylage	37.6	0.34	--	--	16.2	0.27
Corn grain	7.8	0.21	4.2	0.27	4.2	0.26
Protein mix	3.0	0.77	--	--	--	--
Corn silage	8.4	0.22	9.6	0.23	11.5	0.21
Mineral mix	0.4	4.15	0.5	4.15	--	
Corn gluten	--	--	4.8	0.88	--	
DDGS	--	--	--	--	4.26	1.52
Pasture[1]	--	--	20.0	0.25	--	--
Whole diet		*0.35*		*0.37*		*0.39*
			Edgar Cows			
TMR	38.8	0.37	16.3	0.33	23.3	0.41
Grain mix	--	--	7.1	0.34	--	--
Pasture	--	--	20.0	0.33	20.0	0.26
Whole diet		*0.37*		*0.33*		*0.34*
			Edgar Calves			
TMR	--	--	--	--	1.9	0.72
Hay	--	--	--	--	1.0	0.24
Pasture	--	--	--	--	5.0	0.26
Whole diet						*0.39*
			Athens			
Haylage	24.5	0.20	--	--	9.5	0.36
Protein Mix	6.2	0.73	--	--	--	--
Corn Silage	13.0	0.18	--	--	--	--
Corn grain	12.3	0.24	--	--	--	--
Mineral mix	1.6	1.09	--	--	--	--
Pasture	--	--	20	0.33	5.0	0.26
TMR	--	--	21.8	0.30	61.1	0.42
Whole diet		*0.29*		*0.31*		*0.40*

[1]Amounts of pasture consumed are estimated from UW Extension information.

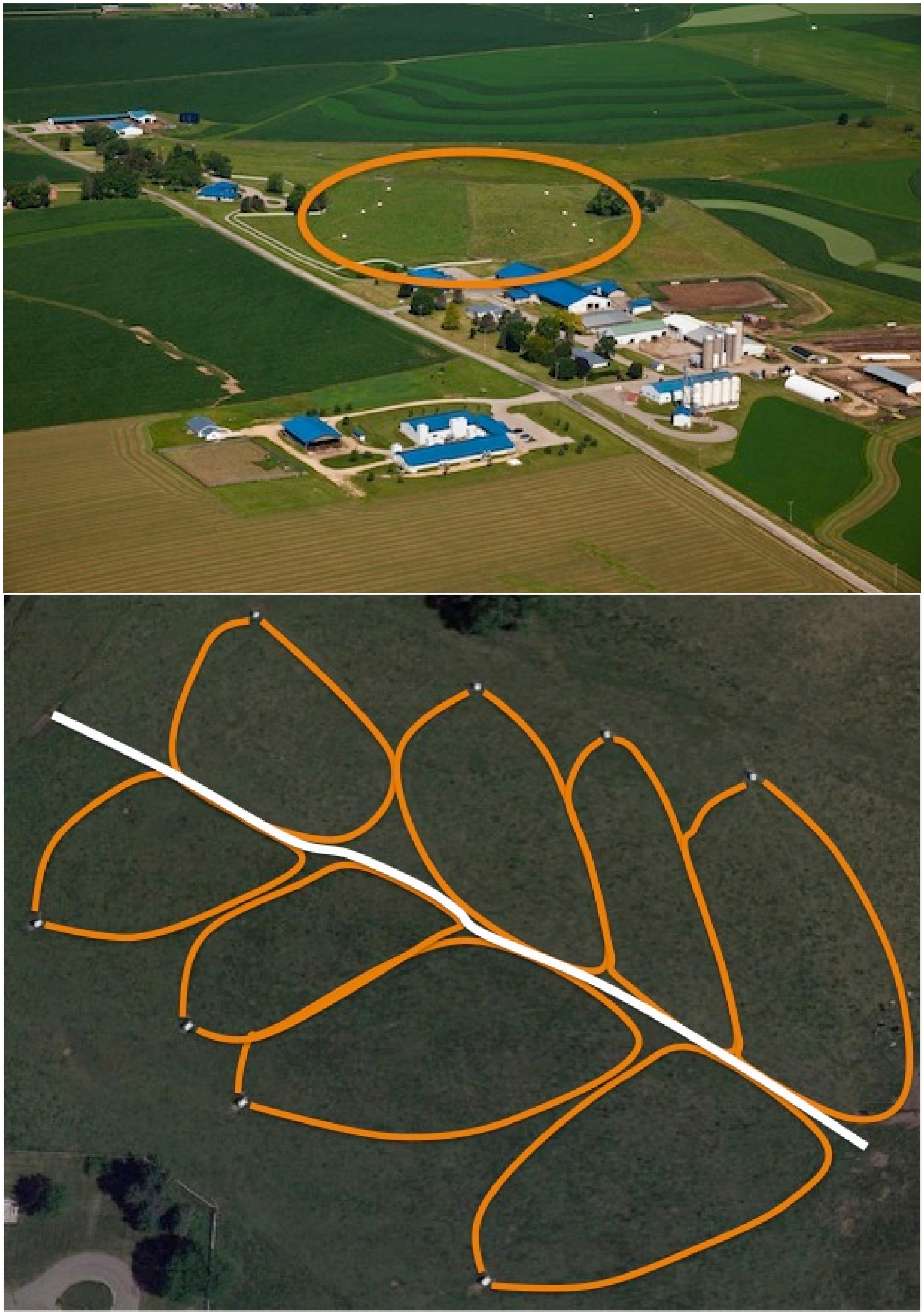
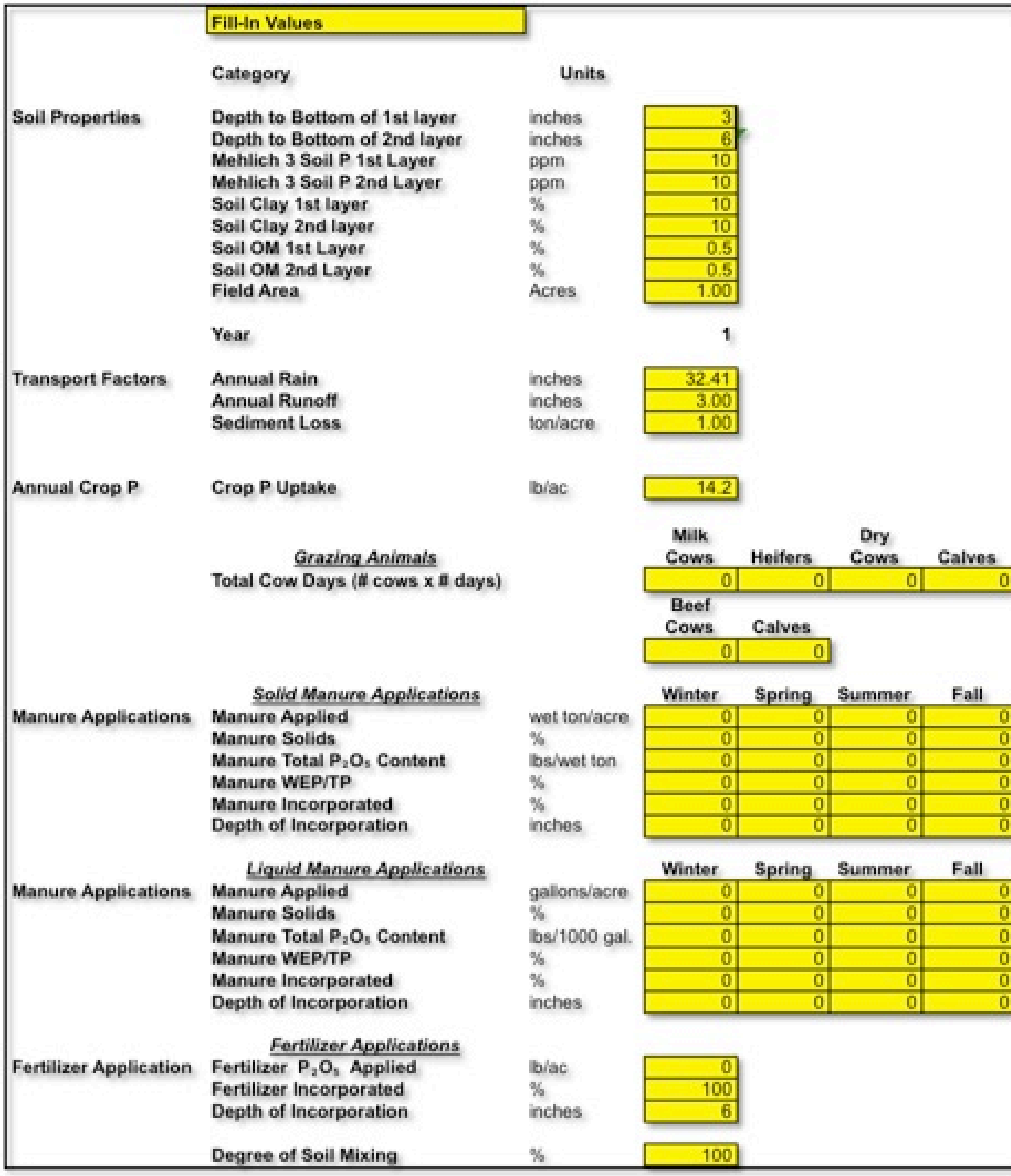


Figure 1. Aerial photo of the 8 pasture basins at the Pioneer farm with the basin boundaries delineated. The white boxes at the end of the delineations are the runoff collection locations.



	Fill-In Values					
	Category	Units				
Soil Properties	Depth to Bottom of 1st layer	inches	3			
	Depth to Bottom of 2nd layer	inches	6			
	Mehlich 3 Soil P 1st Layer	ppm	10			
	Mehlich 3 Soil P 2nd Layer	ppm	10			
	Soil Clay 1st layer	%	10			
	Soil Clay 2nd layer	%	10			
	Soil OM 1st Layer	%	0.5			
	Soil OM 2nd Layer	%	0.5			
	Field Area	Acres	1.00			
	Year		1			
Transport Factors	Annual Rain	inches	32.41			
	Annual Runoff	inches	3.00			
	Sediment Loss	ton/acre	1.00			
Annual Crop P	Crop P Uptake	lb/ac	14.2			
	Grazing Animals		Milk Cows	Heifers	Dry Cows	Calves
	Total Cow Days (# cows x # days)		0	0	0	0
			Beef Cows	Calves		
			0	0		
	Solid Manure Applications		Winter	Spring	Summer	Fall
Manure Applications	Manure Applied	wet ton/acre	0	0	0	0
	Manure Solids	%	0	0	0	0
	Manure Total P_2O_5 Content	lbs/wet ton	0	0	0	0
	Manure WEP/TP	%	0	0	0	0
	Manure Incorporated	%	0	0	0	0
	Depth of Incorporation	inches	0	0	0	0
	Liquid Manure Applications		Winter	Spring	Summer	Fall
Manure Applications	Manure Applied	gallons/acre	0	0	0	0
	Manure Solids	%	0	0	0	0
	Manure Total P_2O_5 Content	lbs/1000 gal.	0	0	0	0
	Manure WEP/TP	%	0	0	0	0
	Manure Incorporated	%	0	0	0	0
	Depth of Incorporation	inches	0	0	0	0
	Fertilizer Applications					
Fertilizer Application	Fertilizer P_2O_5 Applied	lb/ac	0			
	Fertilizer Incorporated	%	100			
	Depth of Incorporation	inches	6			
	Degree of Soil Mixing	%	100			

Figure 2. Illustration of the input screen for the APLE model.

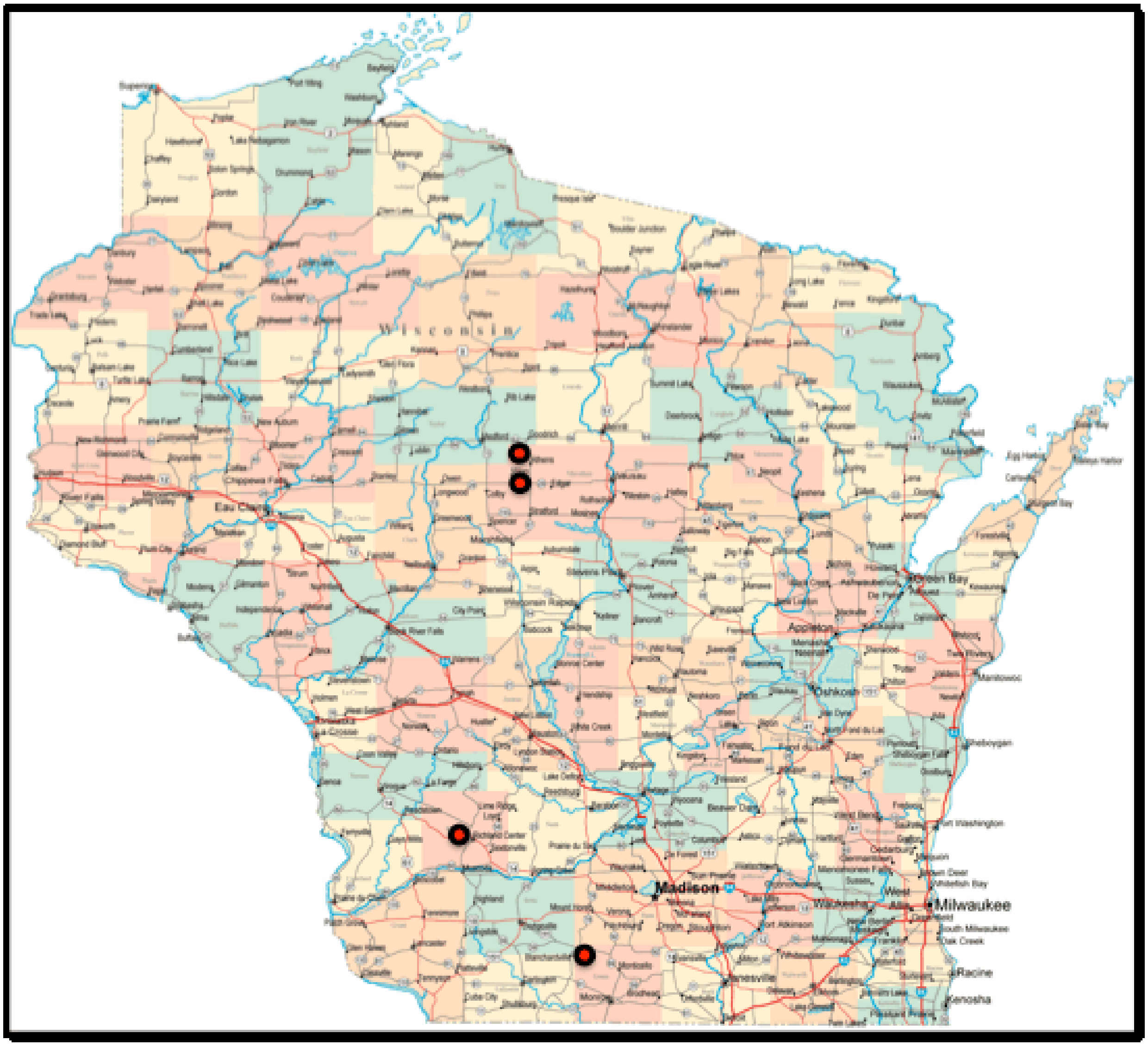


Figure 3. Location of the four grazing farms in WI.

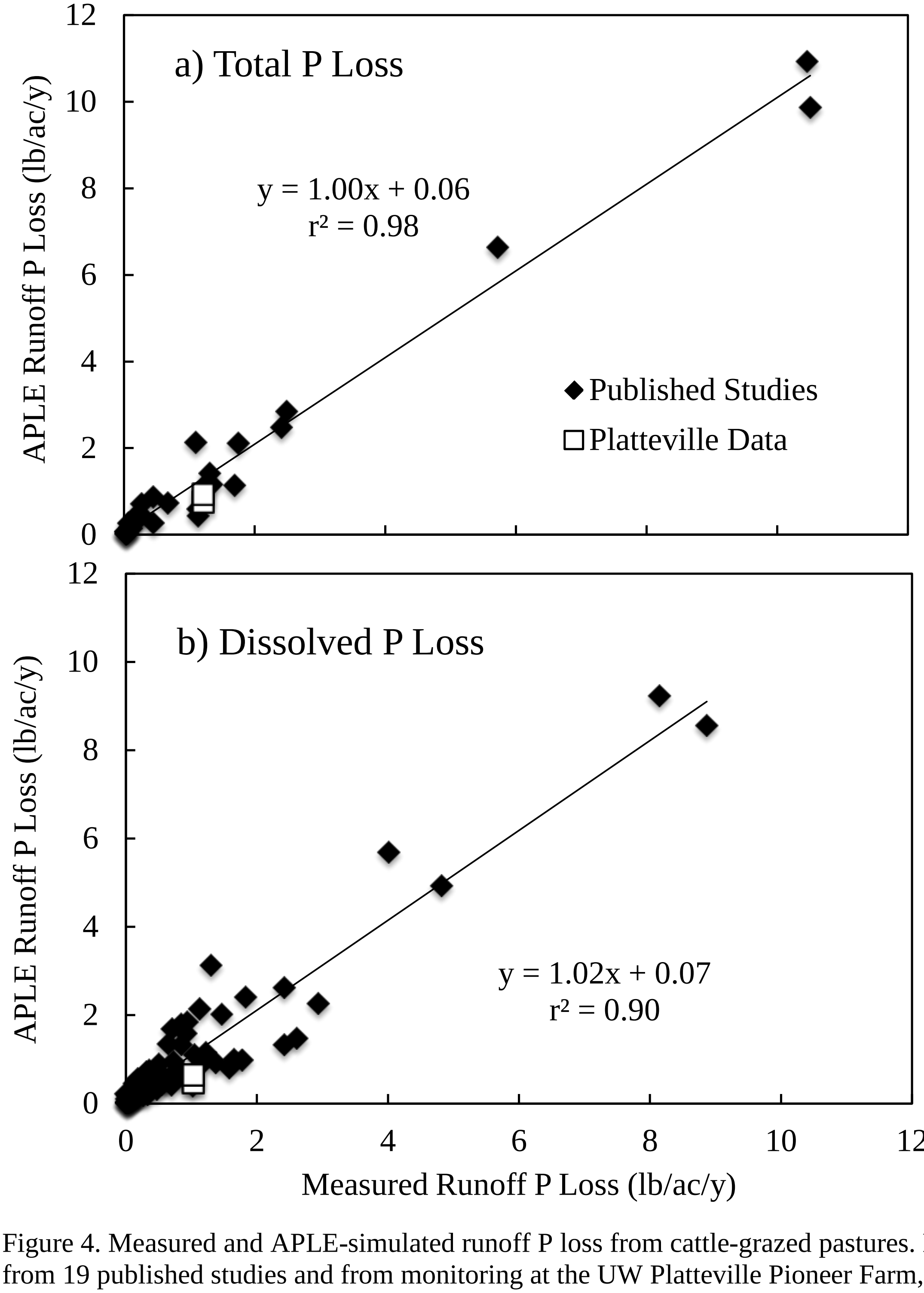


Figure 4. Measured and APLE-simulated runoff P loss from cattle-grazed pastures. Data are from 19 published studies and from monitoring at the UW Platteville Pioneer Farm, for a) Total P in loss (n=33) and b) Dissolved P loss (n=82).

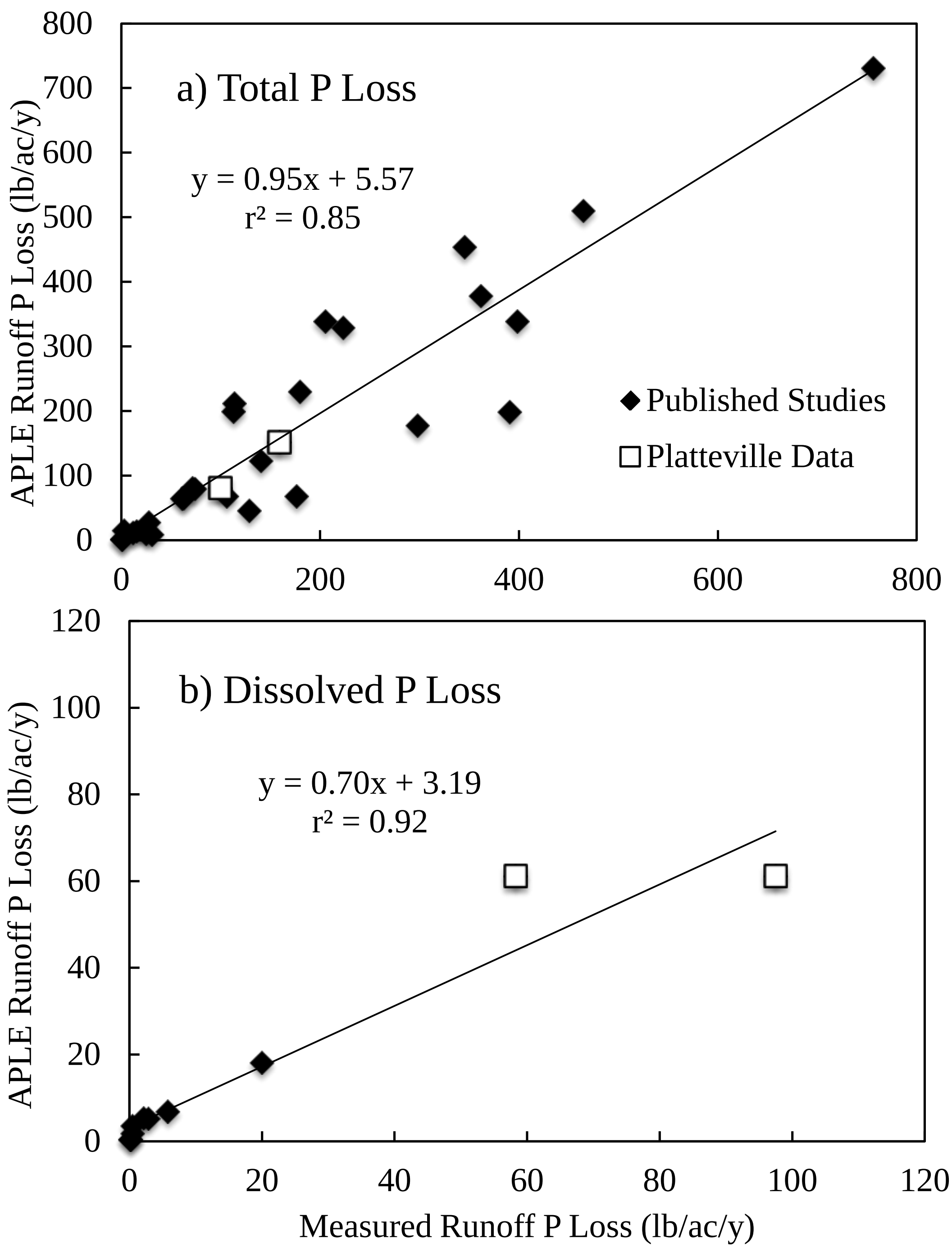


Figure 5. Measured and APLE-simulated runoff P loss from cattle feedlots and barnyards. Data are from 12 published studies and from monitoring at the UW Platteville Pioneer Farm, for a) Total P in loss (n=33) and b) Dissolved P loss (n=12).

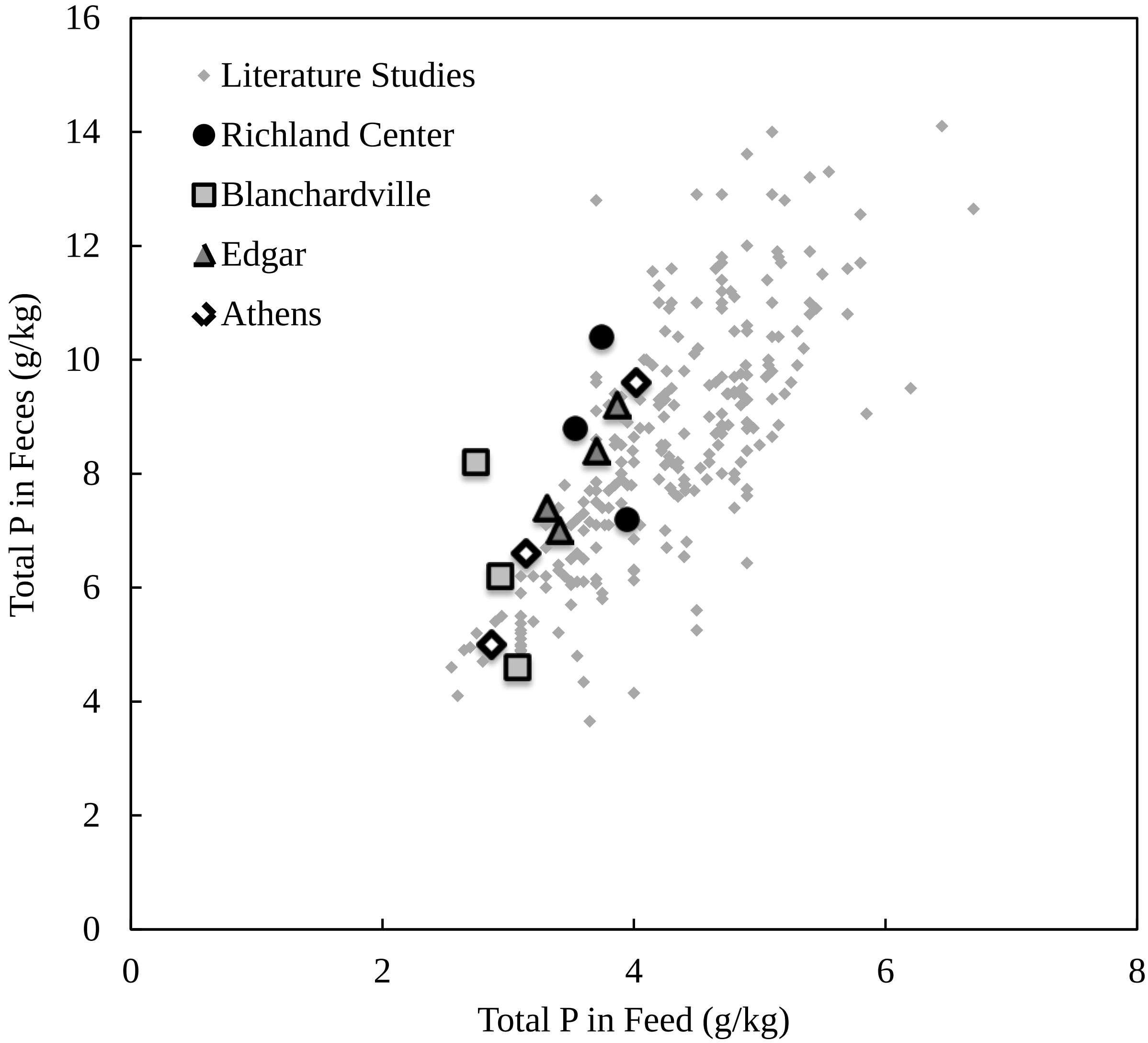


Figure 6. Relationship between total P content of lactating cow feed and cow feces. Data are from the four WI grazing farms and from 12 studies in the published literature.

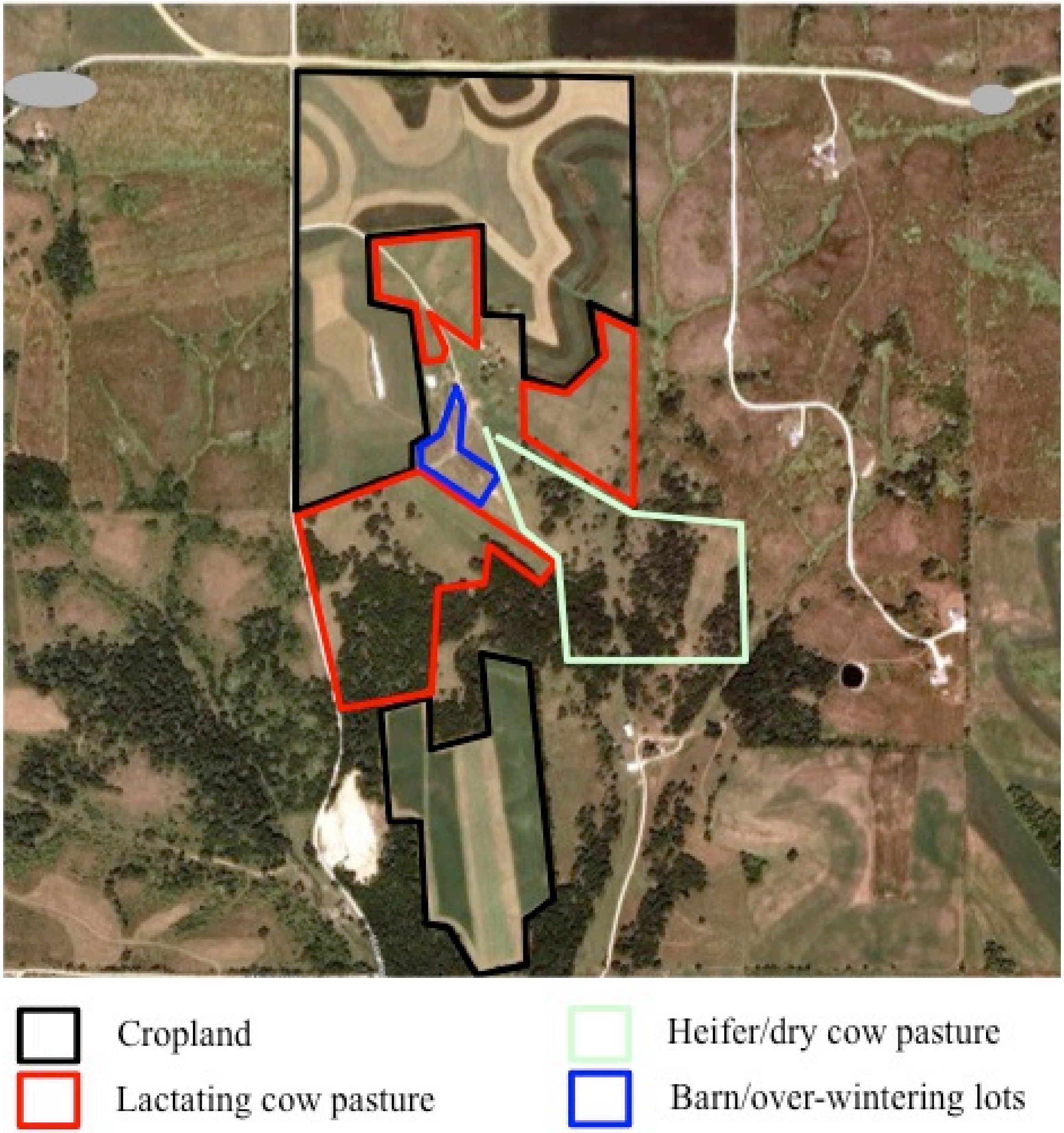


Figure 7. View of the Blanchardville grazing farm.

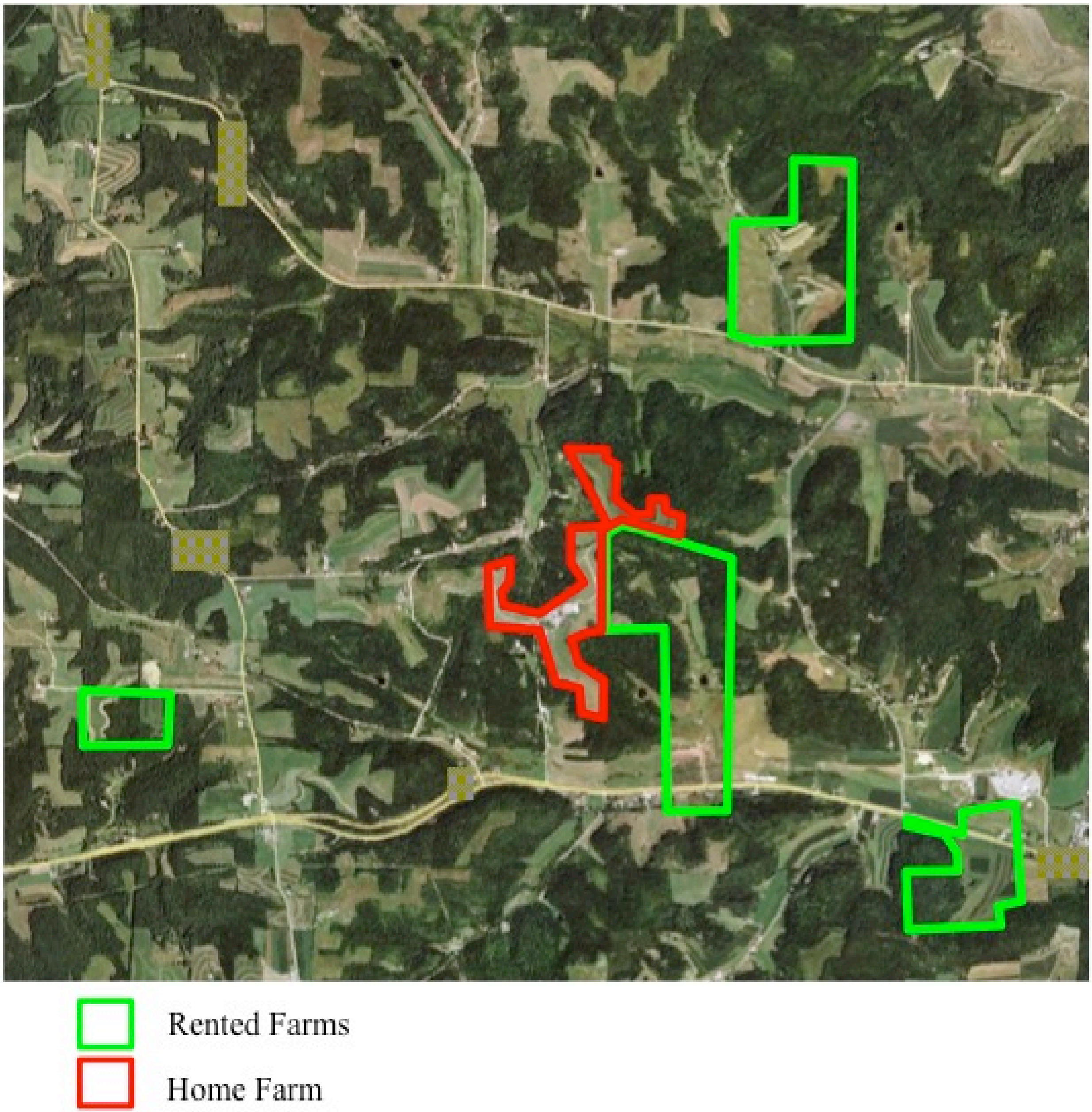


Figure 8. Location of the home farm and rented farms for the Richland Center farms.

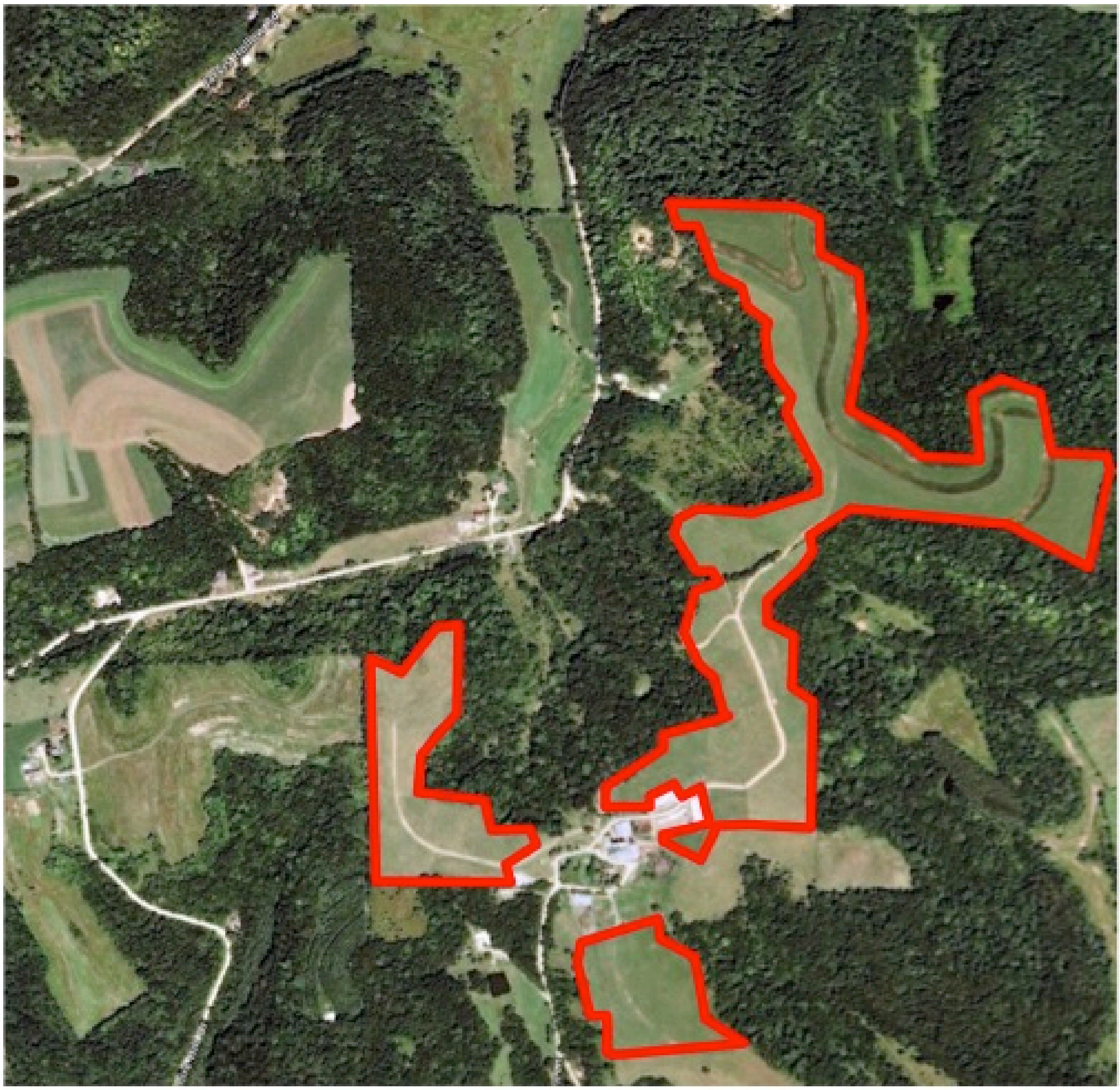


Figure 9. View of the Richland Center home farm, showing pastures for lactating cows.

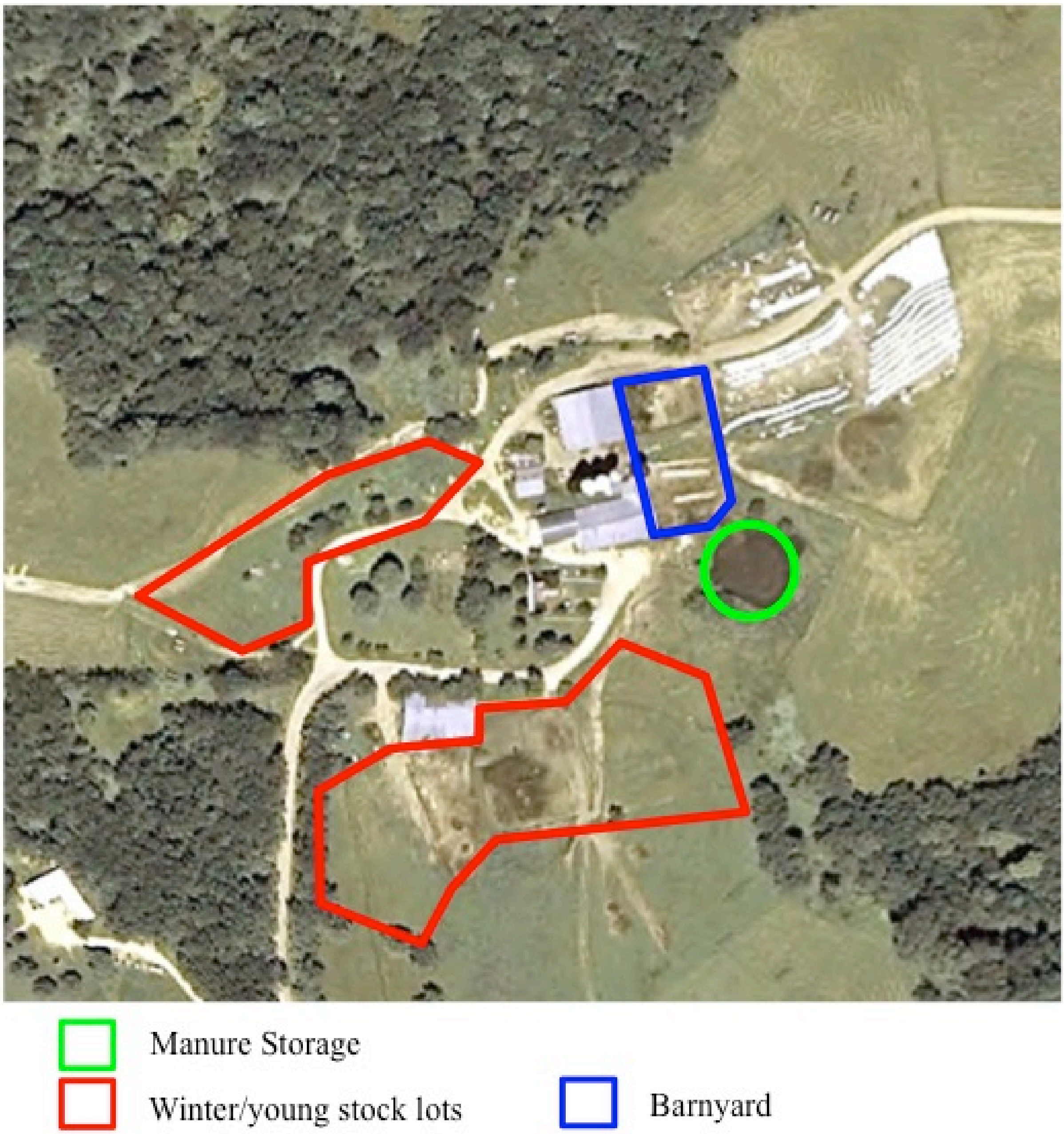


Figure 10. Close-up view of the Richland Center home farm, showing cattle lots, barnyards, and manure storage pit.

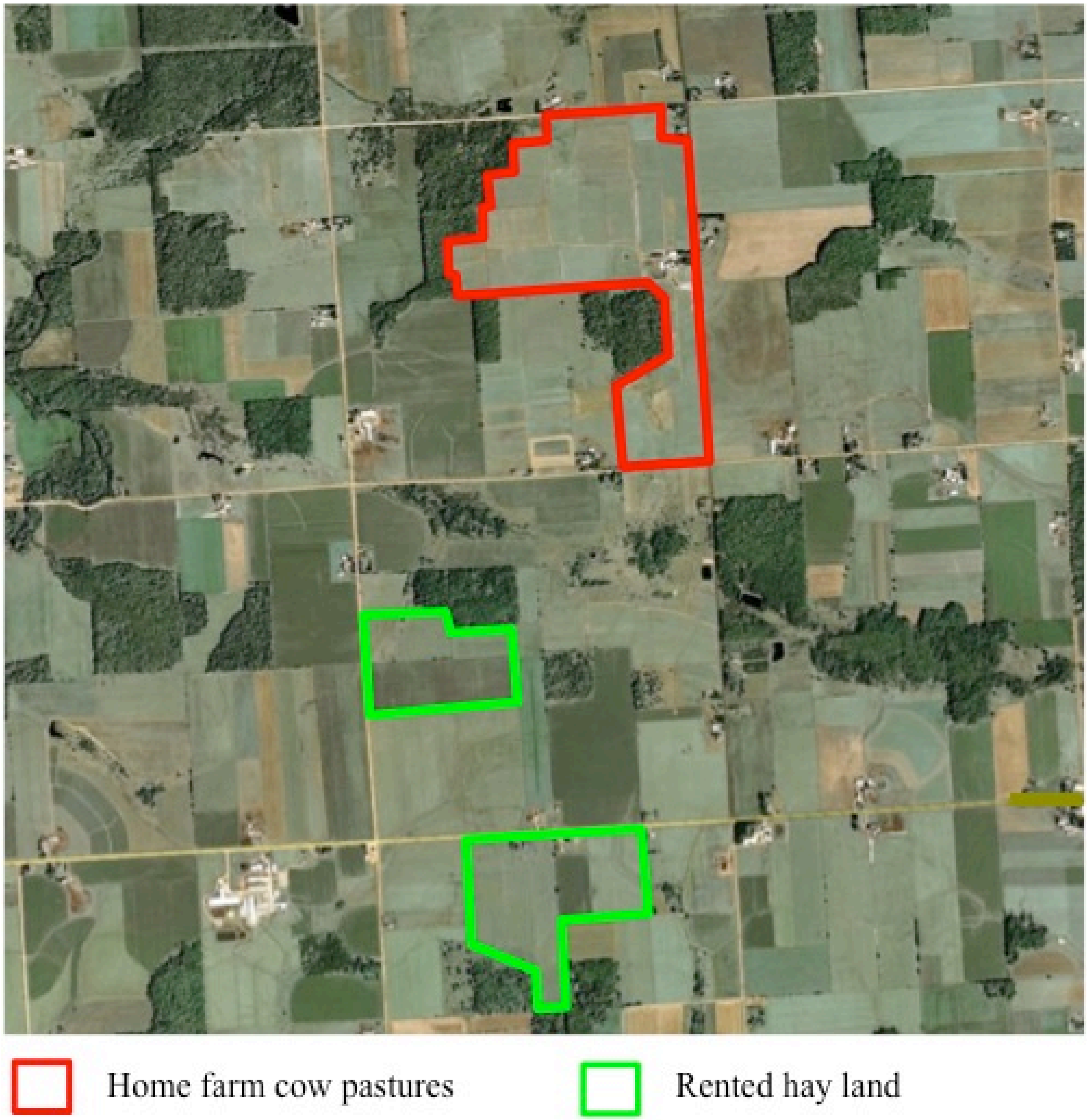


Figure 11. View of the Edgar farm, showing home-farm pastures and rented hay land.

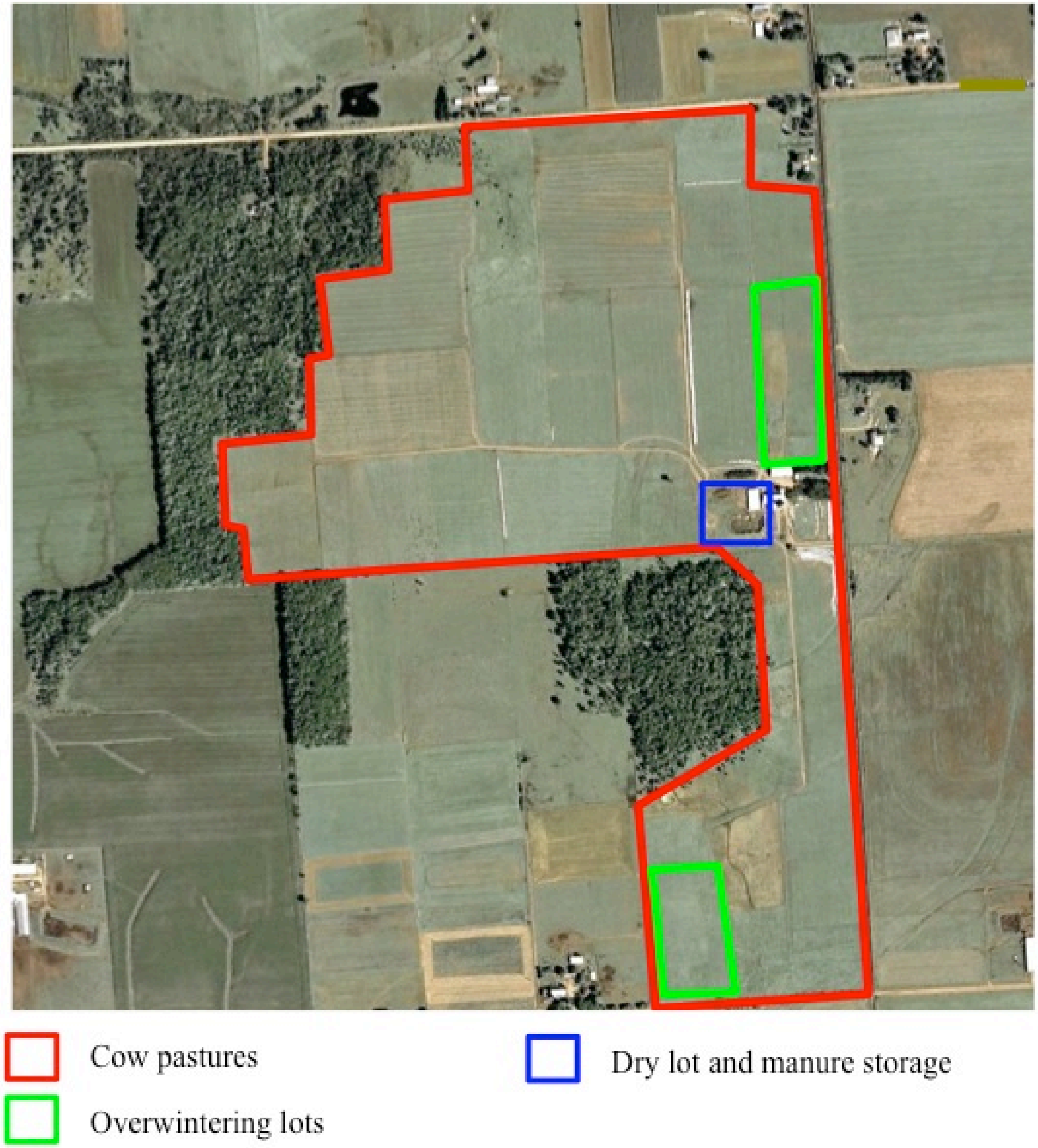


Figure 12. View of the Edgar home farm, showing pastures, wintering lots, dry lot, and manure storage.

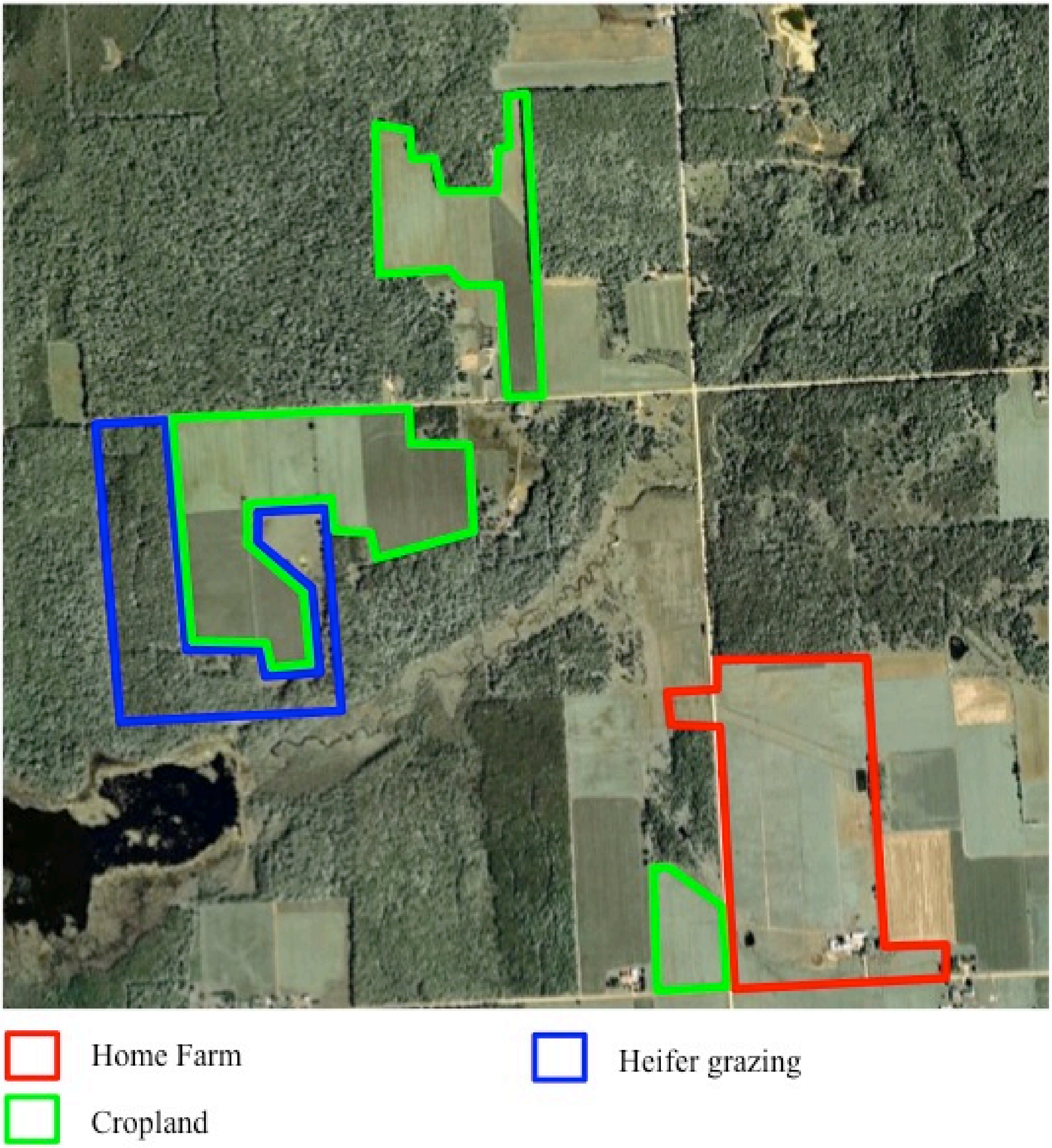


Figure 13. View of the Athens farm, showing home farm, cropland, and nearby heifer grazing area.

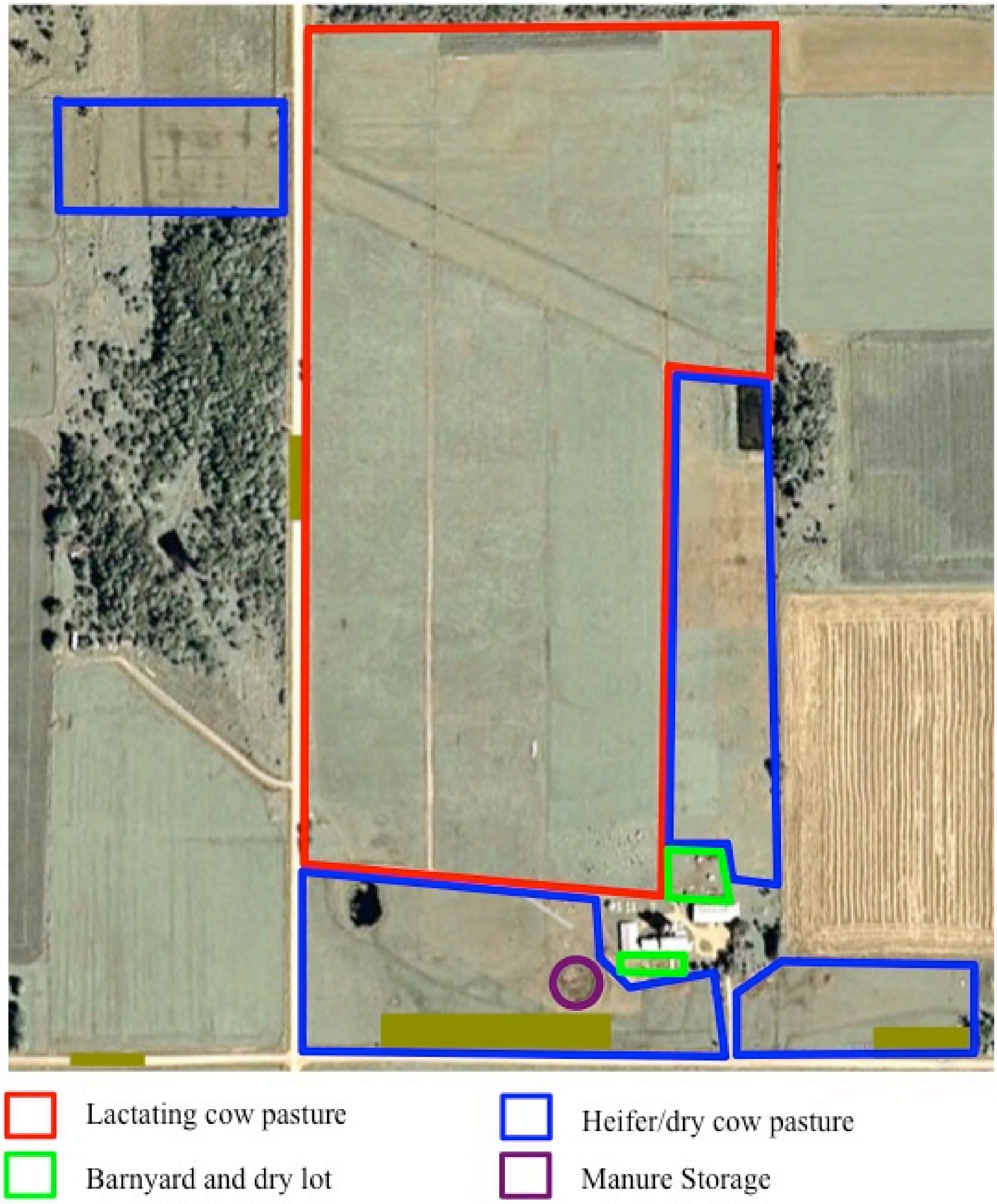


Figure 14. View of the Athens home farm, showing pastures, barnyard and dry lot, and manure storage.

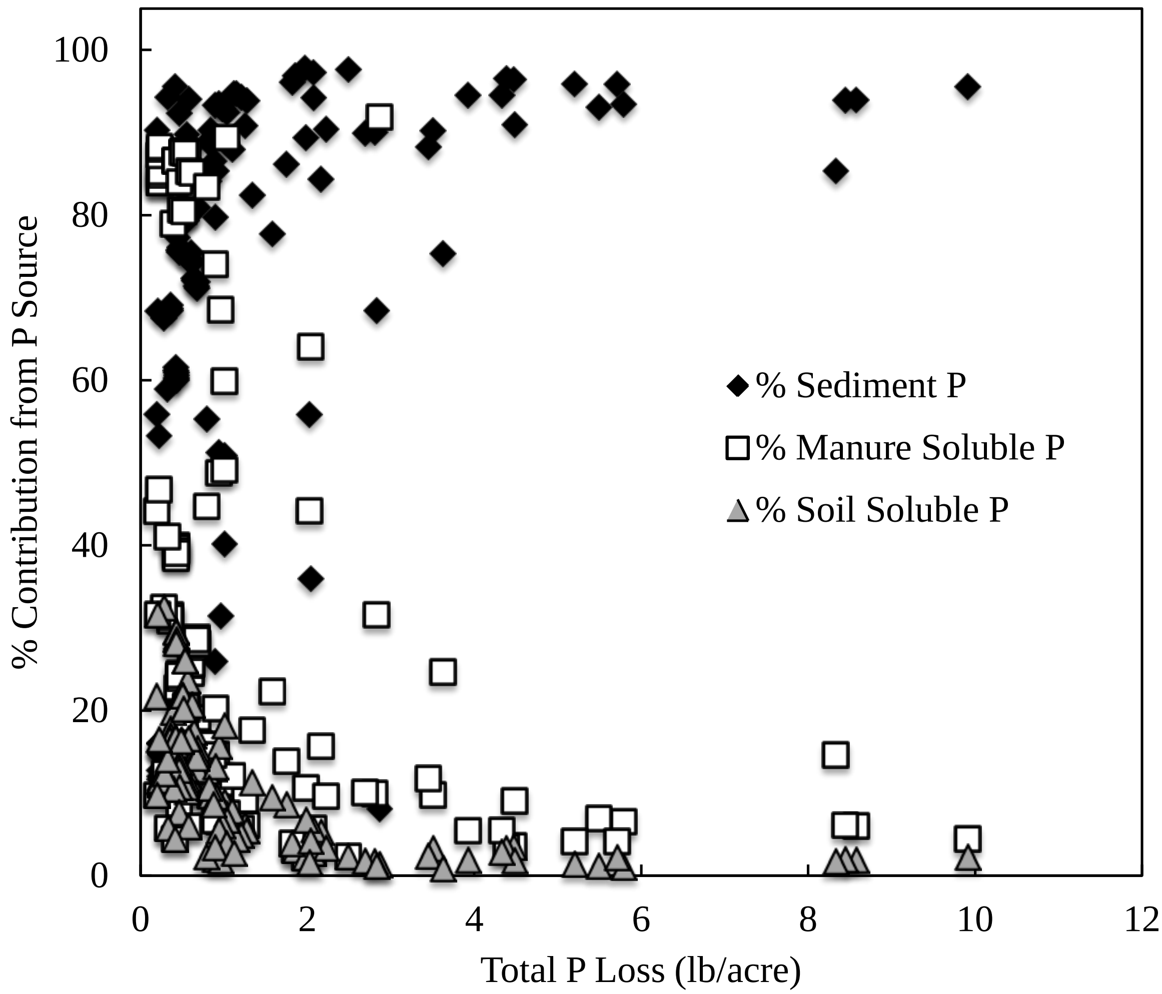


Figure 15. Data from APLE farm simulations showing the relationship between Total P loss and the % contribution from erosion, manure, or soil. These data exclude barnyards and other cattle lots.

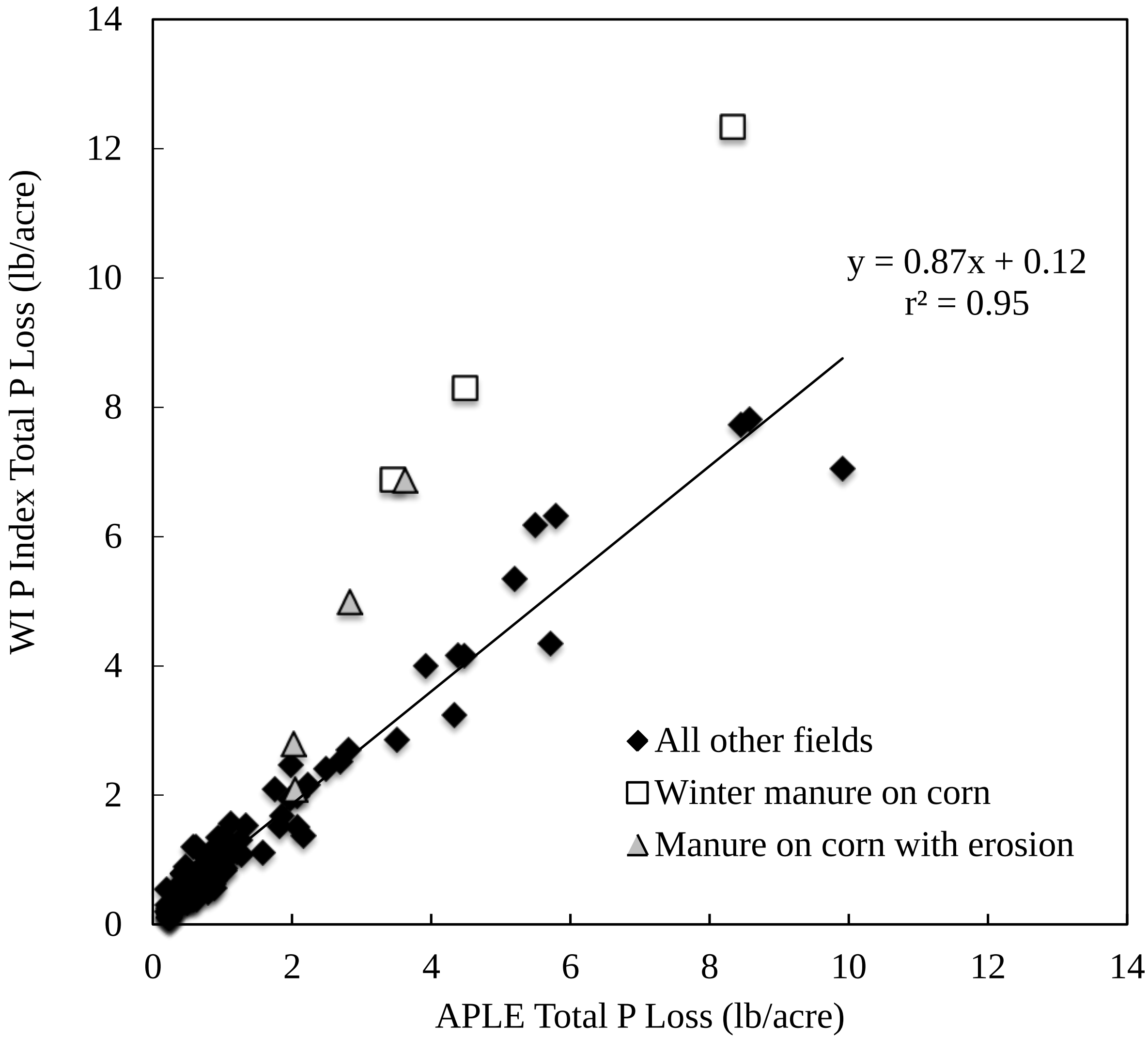


Figure 16. Data from APLE and WI P Index farm simulations showing the relationship between total P loss estimates from the two models. These data exclude barnyards and other cattle lots.

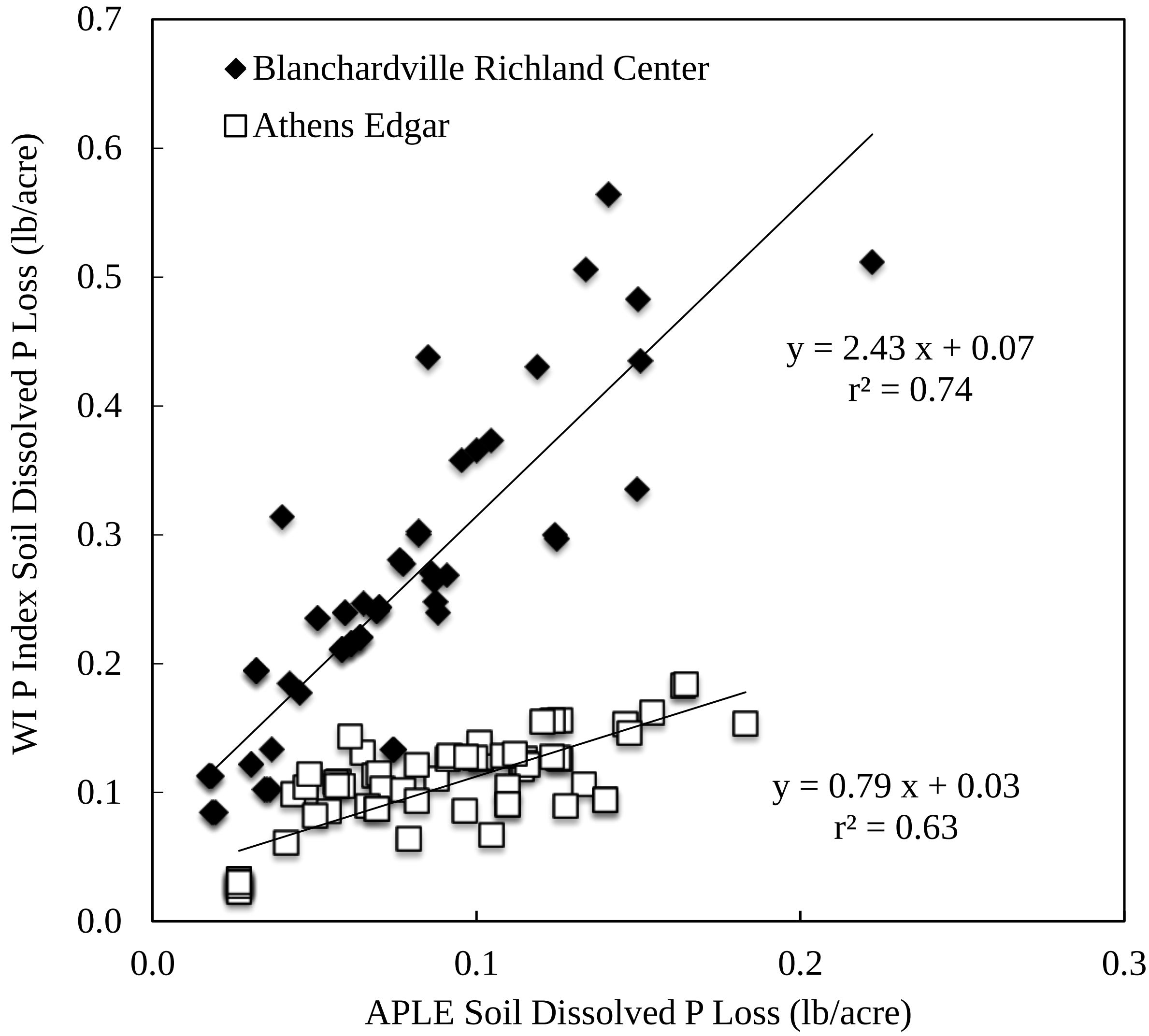


Figure 17. Data from APLE and WI P Index farm simulations showing the relationship between estimates of dissolved P loss from soil for the two models. These data exclude barnyards and other cattle lots.

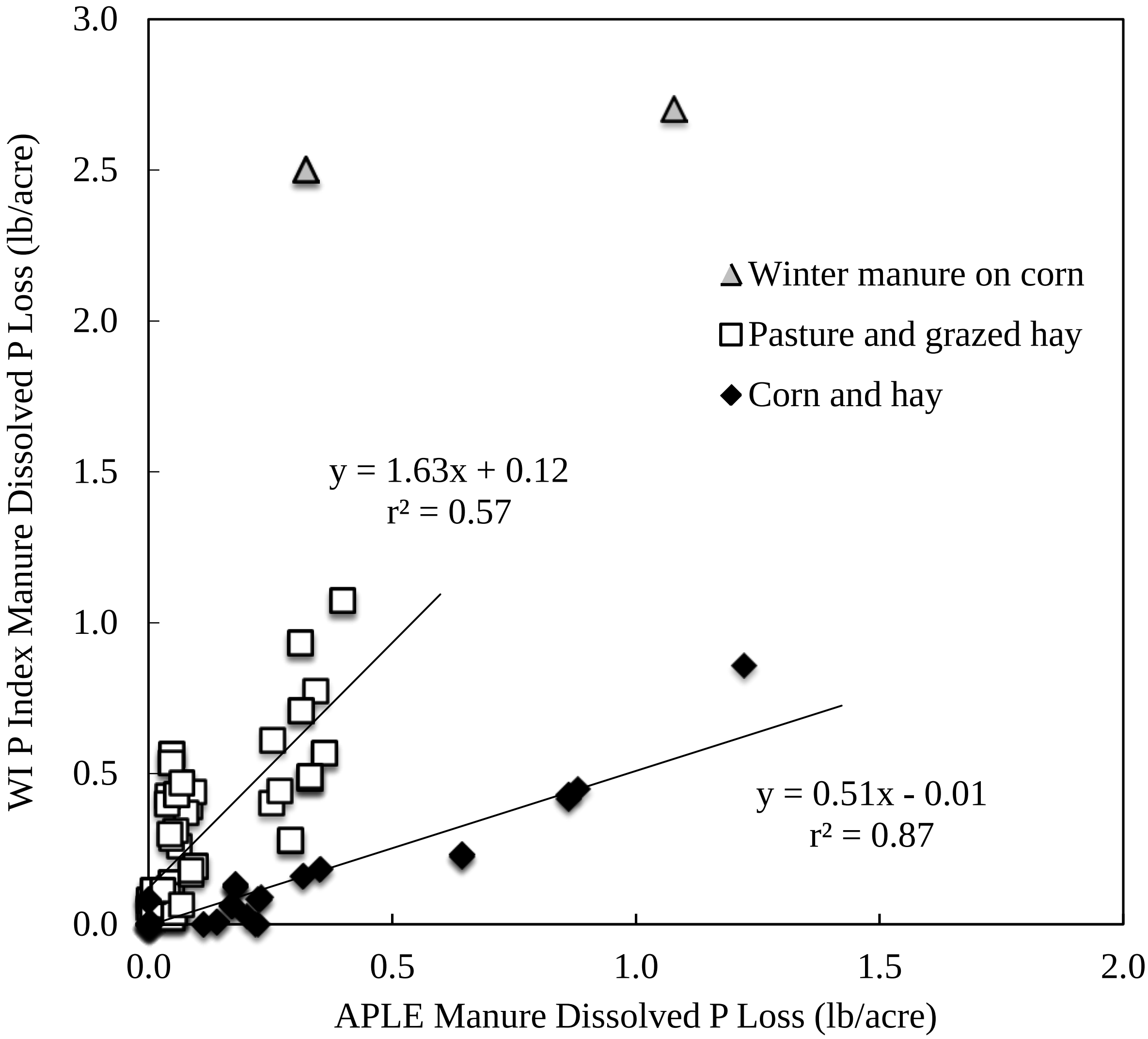


Figure 18. Data from APLE and WI P Index farm simulations showing the relationship between estimates of dissolved P loss from manure on the surface for the two models. These data exclude barnyards and other cattle lots.